

Modeling heavy air  
pollution in Beijing

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# A modeling analysis of a heavy air pollution episode occurred in Beijing

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## Abstract

Because concentrations of fine particulate matter (PM) and ozone in Beijing often exceed healthful levels, China is taking steps to improve Beijing's air quality for the 2008 Olympic Games. In this paper the Models-3 Community Multiscale Air Quality (CMAQ) Modeling System was used to investigate a heavy air pollution episode in Beijing during 3–7 April 2005. The modeling domain covered from East Asia with four nested grids with 81 to 3 km horizontal resolution focusing on urban Beijing. This was coupled with a regional emissions inventory with a 10 km resolution and a local 1 km Beijing emissions database. The trend of predicted concentrations of various pollutants agreed reasonably well with the observations and captured the main features of this heavy pollution episode. The simulated column concentration distribution of PM was correlated reasonably with the MODIS remote sensing products. Control runs with and without Beijing emissions were conducted to quantify the contributions of non-Beijing sources (NBS) to the Beijing local air pollution. The contributions of NBS to each species differed spatially and temporally with the order of  $PM_{2.5} > PM_{10} > SO_2 > SOIL$  for this episode. The percentage contribution of NBS to fine particle ( $PM_{2.5}$ ) in Beijing was averaged about 40%, up to 80% at the northwest of urban Beijing and only 10–20% at southwest. The spatial distribution of NBS contributions for  $PM_{10}$  was similar to that for  $PM_{2.5}$ , with a slightly less average percentage of about 30%. The NBS contributions for  $SO_2$  and SOIL (diameter between  $2.5 \mu m$  and  $10 \mu m$ ) were only 10–20% and 5–10%. In addition, the pollutant transport flux was calculated and compared at different levels to investigate transport pathway and magnitude. It was found that the NBS contribution correlated with the transport flux, contributing 70% of  $PM_{10}$  concentration in Beijing at the time of transport flux peak during a strong episode with a transport path from southwest to northeast.

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## 1 Introduction

Regional air pollution over Mega-city clusters has been accompanied with the quick economical expansion in China. Mega-cities are significant sources of aerosols and oxidants, which are important atmospheric components having direct impacts on air quality and climate on a regional and even global scale. It is critical to understand the key chemical and physical processes controlling the concentrations of these species in these polluted regions. As a research hotspot, one of the dominant mega-city clusters is located in Beijing, the capital of China, and its surroundings areas (Fig. 1). With a population more than 14 million, Beijing's economy growth has been rapidly growing with an annual increasing rate exceeding 10% continuously. For example, the total energy consumption is increased from 38.5 million ton standard coal in 1999 to 45.1 million-ton standard coal in 2002, resulting in a very serious air pollution problem. After Beijing succeeded in the competition for the bid to host the 2008 Olympic Games, improving the air quality in Beijing has been one of the most important tasks for the Chinese government. After a series of air antipollution measures including increasing the natural gas supply, centralizing the heat supply, removing electric heat devices, and using of low sulfur coals, air quality in Beijing has improved obviously since 1997. The number of days of meeting Air Pollution Standard II or better increased from 56 days in 1998 to 254 days in 2005. However, the average concentration of main contaminants remained high in the past three years, indicating that emissions controls only in Beijing are not enough to solve the regional pollution problems over Beijing.

Several studies pointed out that the regional air pollution in Beijing was caused not only by local sources but also significantly by non-Beijing sources (Zhang et al., 2004; Xu et al., 2004; Sun et al., 2004). The basin-like geophysical feature of urban Beijing and its unique weather system are the dominant factors influencing air quality (Ren et al., 2004). Su et al. (2004) investigated certain transport pathways of NBS to Beijing and found that a convergence zone of air pollutants occurred within the atmospheric boundary layer along the combination of the Yanshan-Taihang mountains and the North

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China Plain. The contribution of various emission sources shows a specific structure in spatial distribution and depends on the location and weather system.

In order to improve air quality in Beijing with comprehensive measures, it is necessary to quantitatively evaluate the contribution of NBS so that regional emissions can be controlled more efficiently. This can be achieved through a regional air quality modeling system. Yan et al. (2005) made a long-term simulation of SO<sub>2</sub> and discussed the impacts of different types of sources on air quality. The transport of pollutants among several cities in North China was investigated by Zhang et al. (2004) with simplified chemical transport model, which considered no chemical reactions in simulating PM<sub>10</sub>.

In this study the formation process of a typical heavy air pollution episode in Beijing during 2–7 April 2005 was investigated with the Models-3/CMAQ. This episode clearly showed the typical evolution process of high particle pollution over Beijing with continuous several days' pollution. The temporal and spatial characteristics of the main contaminants were analyzed with a focus on the contributions of NBS to SO<sub>2</sub>, PM<sub>10</sub> and PM<sub>2.5</sub> concentrations in Beijing. The modeling results were also compared with observations of SO<sub>2</sub> and particle matters at a 325 m meteorological tower located on the campus of the Institute of Atmospheric Physics (IAP), meteorological data observed at six monitoring sites in Beijing, and satellite aerosol remote sensing results from NASA.

## 2 Observations and regional patterns of the high air pollution episode

### 2.1 Air Pollution Index (API) of Beijing and surrounding cities

Air Pollutant Index (API) is issued every day by SEPA (State Environment Protection Agency of China) with the monitoring data of suspended particulate matter (PM<sub>10</sub>), sulfur dioxide (SO<sub>2</sub>), and nitrogen dioxide (NO<sub>2</sub>) (<http://www.sepa.gov.cn>). An index value under 100 indicates the air quality of that monitoring station conforms to the National ambient air quality criteria II. A value over 100 will worsen the allergy symptom of unhealthy people. Figure 2 shows the time series of daily API of Beijing and surrounding

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cities in 2–8 April 2005. An obvious high pollution episode occurred in Beijing with API over 100 lasting more than 4 days from 4–8 April and reaching heavy pollution levels with a maximum API of 350 on 5–6 April.

## 2.2 SO<sub>2</sub> and particles observed at IAP 325 m tower

5 Six platforms were made on the IAP tower for simultaneous collection of samples for analysis of SO<sub>2</sub> and particulate matter. The 43 CTL instruments of high precision impulse fluorescence (USA Thermion Environment Corporation) were used for measuring gas at 8 m, 47 m, 120 m, and 280 m. The RP1400a instruments (USA ANPU) were used for measuring mass concentration of the particles at 8 m and 240 m. The available data shown in Fig. 3 for this study include SO<sub>2</sub> at 47 m and PM<sub>10</sub> at 8 m. From Fig. 3, it can be seen that SO<sub>2</sub> concentrations were high on 4–6 April, with peak value exceeding 60 ppb. Hourly variations of PM<sub>10</sub> has similar patterns with SO<sub>2</sub> (Fig. 3), but with much higher levels reaching 300 μg/m<sup>3</sup> for PM<sub>10</sub> during 4–6 April, respectively.

## 2.3 Meteorological patterns and controlling factors

15 Through the analysis of synoptic meteorological charts for this period, it was found that initial weak winds and stable weather patterns prevailed followed by transport of Asian dust from Inner Mongolia causing the 4-day high of air pollution mixing of anthropogenic pollutants and natural dust particles. Surface synoptic patterns show that from 4–6 April, there is a strong high pressure system located over Yangtze River with the low in Beijing. This kind of surface pattern is unfavorable for pollution to diffuse. By analyzing the variance of average meteorological elements such as pressure (Fig. 3a) and wind speed (Fig. 3b) averaged over six observation stations in Beijing from 4–7 April, it was found that the average surface pressure of the six stations was lower than 1010 hPa. During the period of 4 April, 00:00 to 6 April, 12:00 (Local Time, LT), the average surface 4 wind speed was lower than 2 m/s, which caused pollutions to accumulate and reached heavy pollution levels with an API more than 350 on 5–6 April. Consequently,

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the observed SO<sub>2</sub> and PM<sub>10</sub> concentrations at the IAP site were also very high during this period.

### 3 Model description and validation

The Models-3/CMAQ is developed by the U.S. EPA (Byue et al., 1999) and has been widely used in North America and East Asia. It has successfully applied to investigate the Asian continental outflow of carbon monoxide, ozone, and aerosol sulfate to the western Pacific Ocean (Zhang et al., 2002; Uno et al., 2005; Yamaji et al., 2006).

#### 3.1 Model setup

The NCAR/Penn State Mesoscale Model (MM5) (Grell et al., 1994) was used to generate the meteorological fields for CMAQ. The Sparse Matrix Operator Kernel Emissions (SMOKE) module was applied to prepare the emission inventory and generate gridded emission data for the CMAQ model. The input data for emissions were composed of the regional data from Streets et al. (2004) with 10 km resolution updated from the TRACE\_P emissions inventory and a detailed local source emissions database of Beijing city with 1 km resolution for point, mobile, area, and others sources for SMOKE processing.

Four nested grids at the horizontal resolution of 81 km, 27 km, 9 km and 3 km with the same center located at (35.0° N, 116.0° E) were used for MM5 and CMAQ in this study. The coarse domain covers East Asia with 83×65 horizontal grids and the second domain includes most provinces of North China. The third domain consists of Beijing and the surrounding cities, with the focus of the fourth domain on urban Beijing. There are 12 vertical layers extending from the surface to approximately 12 km in CMAQ, which are reduced from 30 sigma levels of MM5 using the mass-weighted averaging algorithms for reducing the computational costs. Vertical layers of CMAQ are unevenly distributed and surface layer is approximately 35 m.

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The selected simulation period for analysis is from 2 to 8 April 2005, with 10-day spin-up from 23 March. Two experiments were performed to evaluate the contribution of NBS to air quality in Beijing: the base run (BR) with all sources and a control run (CR) with only NBS.

### 5 3.2 Comparison of model results with observation and MODIS AOD

Figure 4 shows the comparison of simulated  $\text{SO}_2$  and  $\text{PM}_{10}$  concentrations with observed data at 47 m ( $\text{SO}_2$ ) and 8 m ( $\text{PM}_{10}$ ) height of IAP tower. The model simulated the magnitude and the diurnal patterns of  $\text{SO}_2$  and  $\text{PM}_{10}$  well. The correlation coefficient of  $\text{SO}_2$  and  $\text{PM}_{10}$  between the model and observation is higher than 0.70 and 0.60 respectively. The model can also simulate the variations of the particles during this episode, but the simulation generally under predicted particle concentrations due to uncertainties in emissions and a lack of dust emission module in the current CMAQ system.

The model results are also compared with MODIS optical depth data. Satellite remote sensing provides a means to derive aerosol distribution at global and regional scales. The Moderate Resolution Imaging Spectroradiometer (MODIS) aboard two of NASA's Earth Observing System (EOS) satellites (Terra and Aqua) began a new era of aerosol remote sensing over land (Chu et al., 2003). Aerosol optical depth (AOD) products from MODIS have been verified by the sun-photometer observations in some regions of China (Li et al., 2003) and used to research air pollution in and around Beijing areas (Li et al., 2005). The researched results show that the MODIS AOD data have high accuracy and can better describe the regional and urban pollution distribution. Figure 5a shows the spatial distribution of MODIS Level 2 products of AOD (Version 4) with 10 km nadir spatial resolution in and around Beijing areas on 3 April, 03:15 Z, 2005. Data over ocean parts are not used for larger uncertainty is usually caused by high concentration of sediment. Regions in the north part of the figure are also blank for the surface is too bright (not covered with dense vegetation) to get precise aerosol retrieval. Figure 5b is the model simulated  $\text{PM}_{10}$  column density of Beijing

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and surrounding areas on 3 April, 03:00 Z, 2005. Compared Fig. 5a with Fig. 5b, it can be seen that at in most areas the distributions patterns of simulated column density are consistent with MODIS AOD. In the coastal areas of Bo Hai Bay, about 200 km away from Beijing, MODIS observed larger AOD values than our model . The difference between the two sources is mainly due to MODIS AOD retrieval errors near estuary and coastal areas with high sediment concentration in the water (Li et al., 2003). AOD values in the Beijing area corresponding to our model grids are derived from MODIS level 2 products according to the nearest valid data within the scope from 39° N to 40.5° N, and from 115.5° E to 117° E. The correlation coefficient between MODIS AOD and model results are higher than 0.90 (R-squared ~0.84) (Fig. 6).

## 4 Results and discussions

### 4.1 Temporal and spatial distribution of simulated PM<sub>10</sub> concentration

Figure 7a shows the simulated altitude-time cross sections of PM<sub>10</sub> concentrations at the IAP site. From 4–6 April of 2005, PM<sub>10</sub> concentrations below 200 m were very high, especially at night, which corresponded to the lower atmospheric boundary layer (ABL) height (Fig. 7b) from 20:00 to 08:00 (LCT), preventing atmospheric pollutants from dispersing away. Also during this period the surface wind speed was very weak especially from 4 April, 17:00 to 5 April, 08:00 and from 5 April, 20:00 to 6 April, 08:00 (LCT) with a wind speed of less than 1.0 m/s (Fig. 3).

### 4.2 NBS contributions to SO<sub>2</sub> and particle in Beijing during the episode

Figure 8 represents the simulated SO<sub>2</sub> and PM10 concentrations in the fourth nested domain (3 km) at 02:00 Z, on 5 April. The horizontal distributions of SO<sub>2</sub> and PM10 are shown in Figs. 8a and c with all sources and in Figs. 8b and d for only NBS, respectively. Figure 8a shows that SO<sub>2</sub> concentrations at most urban Beijing are higher

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than 30 ppb, peaking around at 110 ppb in the west of urban Beijing. Compared with Fig. 8b, the contribution of NBS to  $\text{SO}_2$  in most areas of urban Beijing is about 6 ppb, with higher contributions in southeast area. The patterns of  $\text{PM}_{10}$  concentrations are similar to those of  $\text{SO}_2$ , with a maximum of more than  $210 \mu\text{g}/\text{m}^3$  at west of urban Beijing (Fig. 8c). The contribution of NBS for  $\text{PM}_{10}$  concentration in Beijing is about 10–15  $\mu\text{g}/\text{m}^3$  (Fig. 8d).

The following formula was used to calculate the percentage contributions (PC) from NBS to  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ ,  $\text{SO}_2$  and SOIL (soil particle with diameter between  $2.5 \mu\text{m}$  and  $10 \mu\text{m}$ ):

$$PC = C(CR) \times 100 / C(BR)$$

where  $C(CR)$  and  $C(BR)$  are the simulated concentrations of  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ ,  $\text{SO}_2$  or SOIL, with BR run (all sources) and CR run (only NBS), respectively.

Using the results from the two runs, the distribution patterns of PC for  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  were obtained.  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  generally show similar patterns, indicating the same source regions for both of them. The contributions of NBS are variously distributed over urban Beijing. Detailed contribution ratios of NBS at urban area are summed up in Table 1. The mean contribution of NBS to  $\text{PM}_{2.5}$  is 30–40%, with maximum up to 60% at the southeast of urban and only 15% at southwest Beijing. The spatial distribution for  $\text{PM}_{10}$  is very close to  $\text{PM}_{2.5}$ , but with slightly less values of 5%. The mean contributions of NBS for  $\text{SO}_2$  is about 10–20% with the maximum up to 30% at southeast of urban area, in contrast, the contribution of NBS to SOIL is about 5–10% at most urban area. Table 1 also clearly points out that NBS contributions are different for each pollutant, with the order of  $\text{PM}_{2.5} > \text{PM}_{10} > \text{SO}_2 > \text{SOIL}$  for this episode.

It can also be elucidated from the table that the NBS contribution of fine particles is larger than that of coarse particles to Beijing background PM levels as the fine particles are much easier to be long-range transported.

### 4.3 Pathways of NBS transporting to Beijing

The vertical altitude-time cross section and the west-east cross section of  $PM_{10}$  flux along Beijing are shown in Fig. 9 and Fig. 10, respectively.  $PM_{10}$  flux is calculated by the following formula:

$$\text{flux} = C \times V$$

Where  $C$  is the simulated concentration of  $PM_{10}$  and  $V$  is the wind velocity.

From 3 to 6 April, strong  $PM_{10}$  fluxes were calculated coming from the southwest to the northeast of Beijing, especially during nighttime. The peak  $PM_{10}$  flux was seen at about 14:00 Z on 5 April of 2005, which corresponded to the peak value of contribution percentage to  $PM_{10}$  at this time (Fig. 11). The peak  $PM_{10}$  flux was up to  $1100 \mu\text{g}\cdot\text{m}^2\cdot\text{s}^{-1}$  at an altitude of about 200 m and correspondingly the peak contribution ratio of NBS to  $PM_{10}$  was up to 60%.

Figure 11 shows that the  $PM_{10}$  flux peaks at the same time as the maximum of the contribution to  $PM_{10}$  occurs, with a delayed  $PM_{10}$  concentration peak. At 18:00 Z on 3 April, 15:00 Z on April 4 and at 14Z on April 5, the contribution percentage of NBS was very large with a strong  $PM_{10}$  flux imported from surrounding areas into Beijing, which induced the high  $PM_{10}$  concentration at later time (at 23:00 Z on 3 April, 20:00 Z on 4 April and at 20:00 Z on 5 April). The contribution of surrounding sources plays a very important role in forming high pollution concentration in Beijing during this episode.

From the horizontal distribution chart of  $PM_{10}$  fluxes (Fig. 12), it can be seen that strong particle fluxes were transported from the southwest area of Beijing by southwest wind. At 06:00 Z on 5 April, the flux center located at the boundary of Hebei province from Shanxi province. At 10:00 Z on 5 April, the high flux center moved to the northeast of Shijiazhuang. Later, the flux peak reached Beijing at about 14:00 Z. Therefore, the dominant transport pathway for NBS effecting Beijing was by the west and southwest flow during this episode. Meteorological analysis (Sect. 2.3) shows that during this period, Beijing was controlled by southwest wind on 850 hPa and surface, and located at low pressure on groove. This type of meteorological pattern offers a convenient

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condition for sources located at southwest region to be transported into Beijing. And also after 5 April, the floating dust storms brought by a strong Mongolia cyclone across north China strengthened this process.

## 5 Summary

5 The Models-3/CMAQ coupled with MM5 and SMOKE module was applied to evaluate the contributions of NBS to high SO<sub>2</sub> and particles pollutants in Beijing during 3–7 April 2005. Comparisons of model results with observed data at the IAP tower and MODIS AOD showed that the model captured the main observed features of this serious pollution episode. The correlation coefficient for SO<sub>2</sub> between the model and observed  
10 data was averaged around 0.70 while the correlation coefficient for the modeled column loading of particles and MODIS AOD reached 0.90. The spatial distributions of SO<sub>2</sub> and PM<sub>10</sub> simulated by the model showed that high concentrations were transported from southwest area of Beijing to the northeast by west and southwest winds. This was also confirmed with synoptic chart analysis and transport flux analysis during  
15 this period. The sensitivity studies indicated that NBS contributions varied temporally and spatially for certain pollution species. For PM<sub>2.5</sub>, the largest contribution was up to 80% at the northwest of urban, the least was about 10–20% at southwest. For PM<sub>10</sub>, spatial distribution and temporal variance of contributions were close to those of PM<sub>2.5</sub>, but slightly less. Model results also revealed that NBS contributes more to fine particle than coarse particles. The contributions of SO<sub>2</sub> and SOIL were only 10–20% and 5–10%. The calculated transport flux results show that the PM<sub>10</sub> flux peak and percentage contribution peak of NBS to PM<sub>10</sub> happened almost simultaneously with a delay the PM<sub>10</sub> concentrations.

20 This study presents a well behaved modeling system for investigating the Beijing urban pollutions and source contributions. For a comprehensive analysis of Beijing air pollutions, more observational data are needed for model validations and longer simulations are required to obtain the seasonal variations of NBS contributions.

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**Table 1.** The average percentage contributions of NBS to SO<sub>2</sub> and particle in urban Beijing.

Area	NW	SW	Center	NE	SE	AVE
PM <sub>2.5</sub>	50%	15%	40%	50%	65%	45%
PM <sub>10</sub>	40%	10%	30%	40%	50%	40%
SO <sub>2</sub>	20%	25%	15%	20%	30%	20%
SOIL	5%	10%	5%	5%	10%	5%

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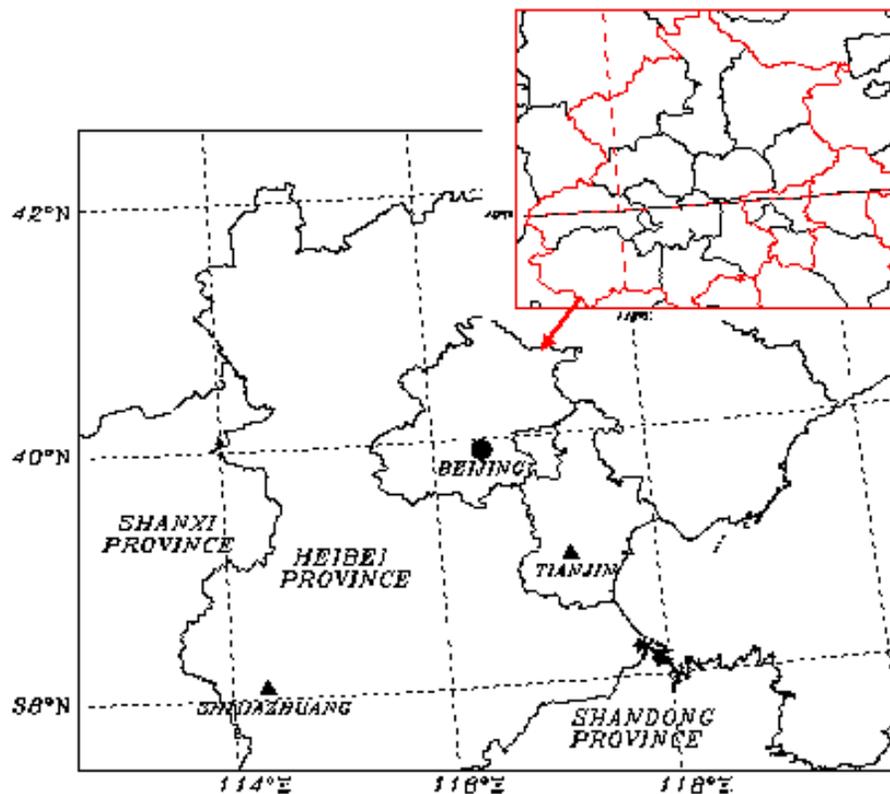
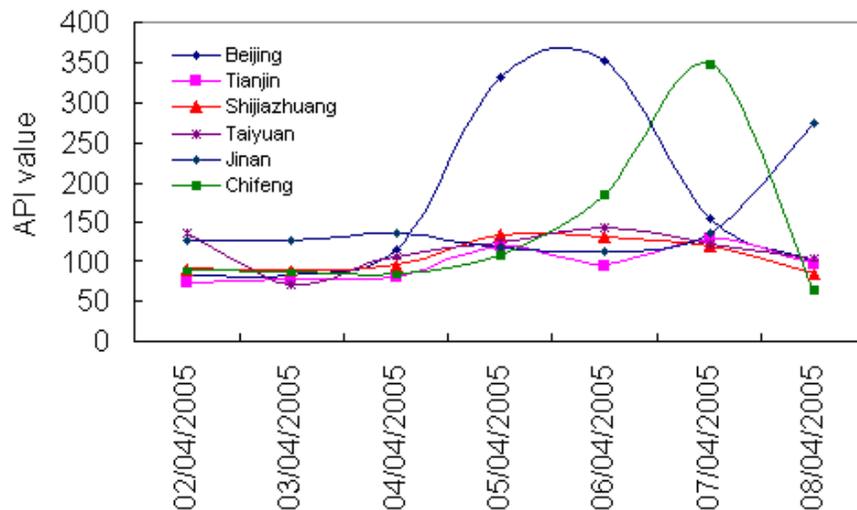


Fig. 1. Map of Beijing and surrounding areas.

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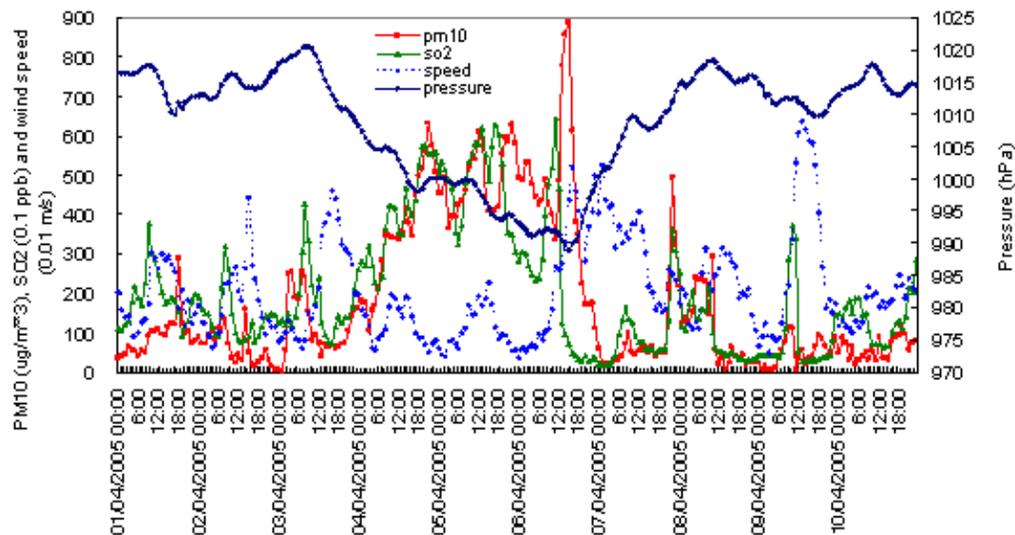
**Fig. 2.** API values of Beijing and surrounding cities from 2 to 8 April 2005.

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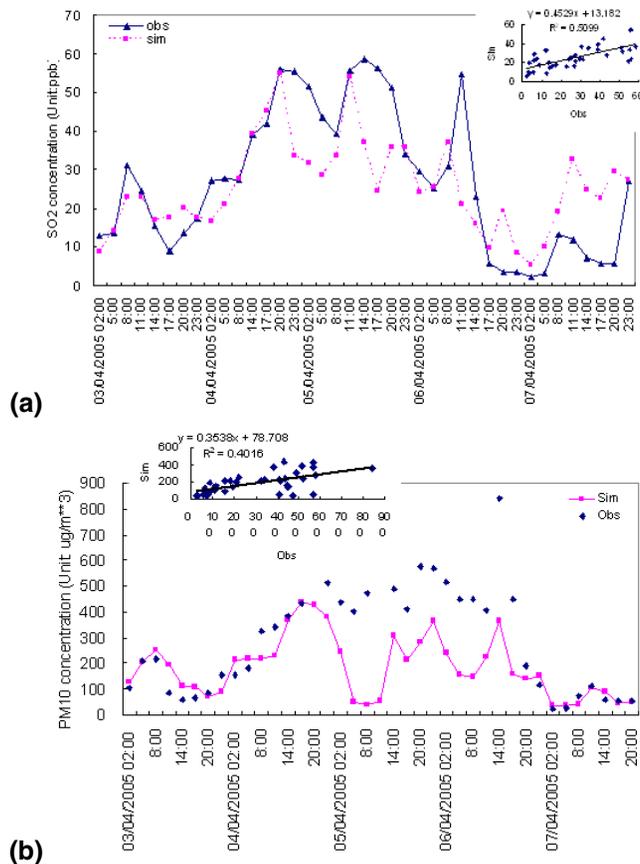
**Fig. 3.** Temporal variations of observed  $\text{SO}_2$  and particle concentrations at IAP site and average pressure, wind speed at six observations sites in Beijing from 1 April 2005 00:00 to 11 April 2005 00:00 (LT).

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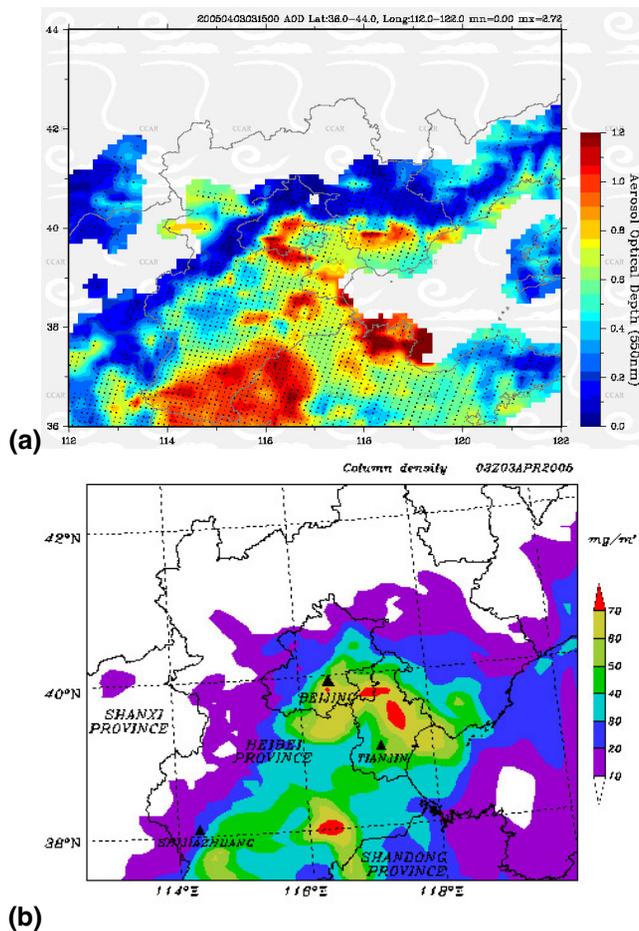
**Fig. 4.** Comparison of observed and simulated SO<sub>2</sub> (a) and PM<sub>10</sub> (b) concentration of three hour average at IAP site from 3 April to 8 April 2005 (LT).

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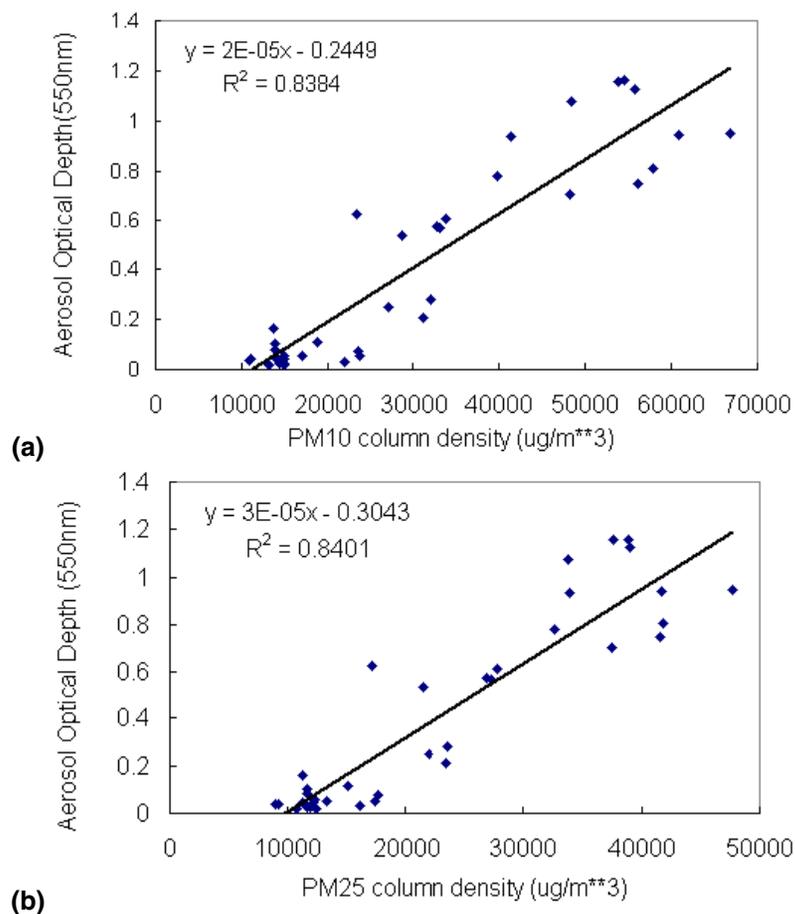


**Fig. 5.** (a) Aerosol Optical Depth spatial distributions by MODIS at 03:15 (UTC) on 3 April 2005  
(b) Model simulated PM<sub>10</sub> column density of Beijing and surrounding areas at 03:00 (UTC) on 3 April 2005.

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**Fig. 6.** Correlation between simulated  $PM_{10}$  (a) and  $PM_{2.5}$  (b) column density with Aerosol Optical Depth.

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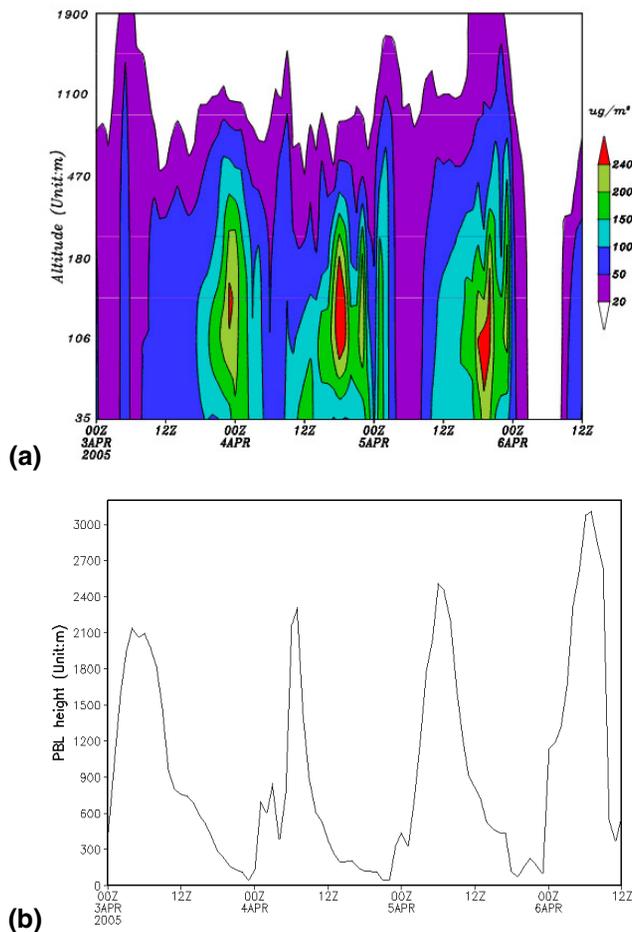
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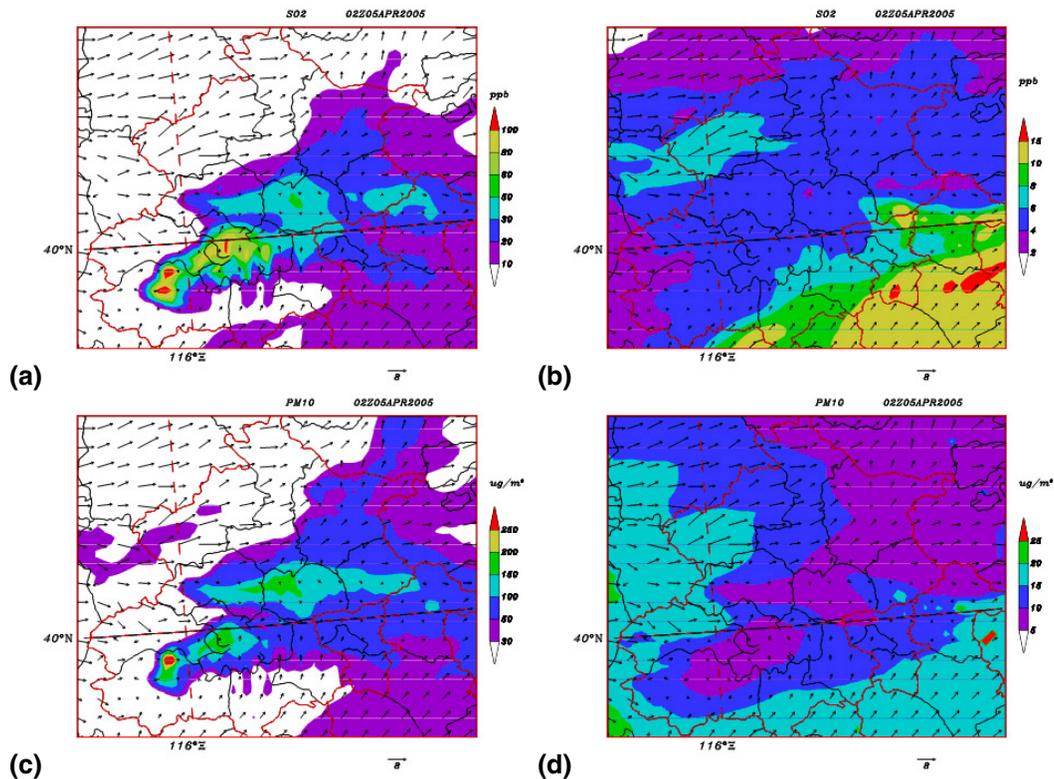


**Fig. 7.** Vertical distributions of simulated PM<sub>10</sub> concentration and calculated atmospheric boundary layer (ABL) height by MM5 along IAP site **(a)** Altitude-time cross sections of PM<sub>10</sub> concentrations **(b)** ABL height.

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**Fig. 8.** Horizontal distributions of simulated SO<sub>2</sub> and PM<sub>10</sub> concentrations over Beijing area at 02:00 (UTC) on 5 April 2005.

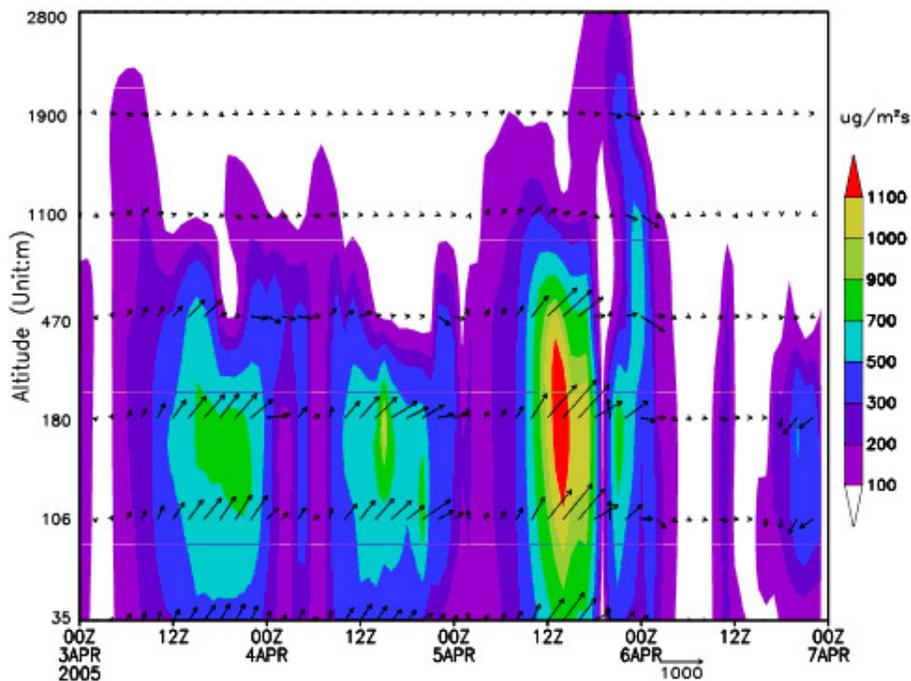
(a) For SO<sub>2</sub> of all sources; (b) for SO<sub>2</sub> of sources outside Beijing; (c) same as (a), but for PM<sub>10</sub>; (d) same as (b), but for PM<sub>10</sub>.

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**Fig. 9.** Altitude-time cross sections of PM<sub>10</sub> flux (Unit:  $\mu\text{g m}^{-2} \text{s}^{-1}$ ) along Beijing from 3 April to 7 April 2005.

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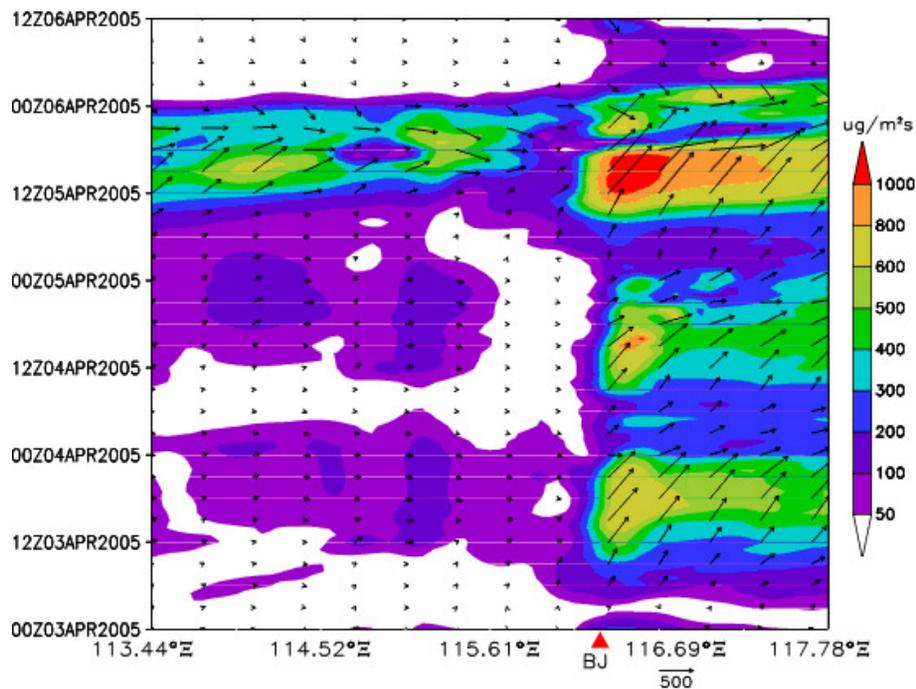
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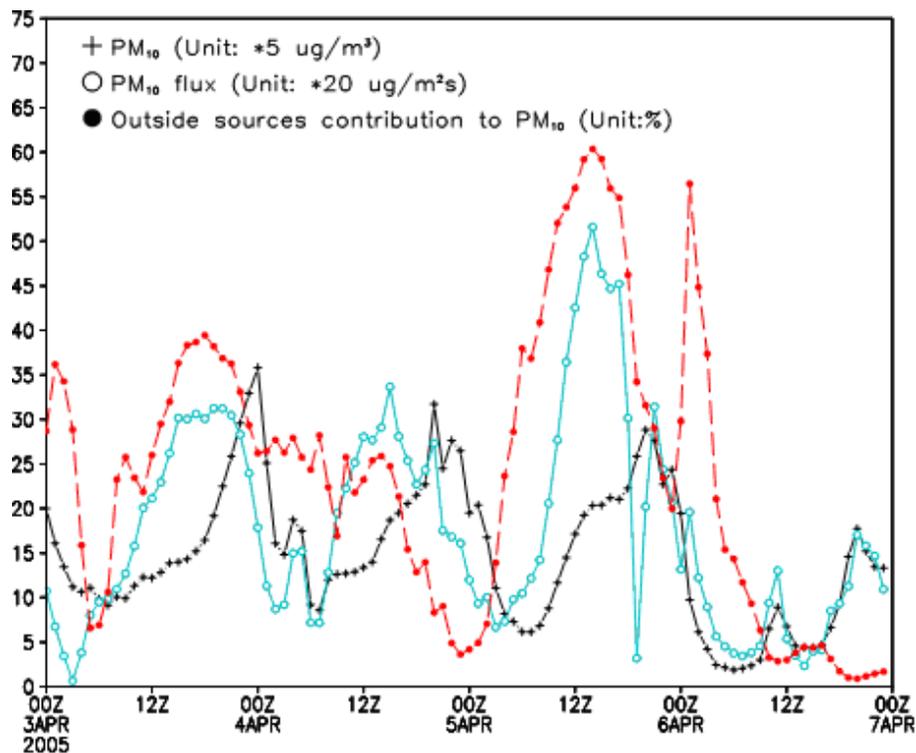
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**Fig. 10.** West-east cross section of PM<sub>10</sub> flux (Unit:  $\mu\text{g m}^{-2} \text{s}^{-1}$ ) along Beijing from 3 April to 6 April.

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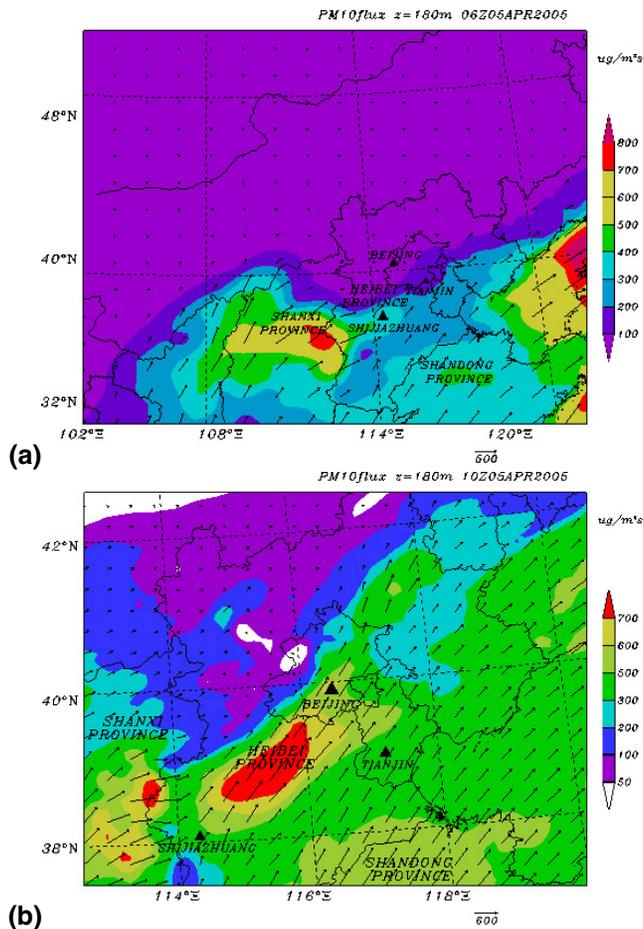
**Fig. 11.** Temporal variance of PM<sub>10</sub> concentration, PM<sub>10</sub> flux ( $\mu\text{g m}^{-2} \text{s}^{-1}$ ) and contribution of sources outside Beijing to PM<sub>10</sub>.

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**Fig. 12.** Horizontal distributions of PM<sub>10</sub>fluxes ( $\mu\text{g m}^{-2} \text{s}^{-1}$ ) on 180 m high at (a) 06:00 (UTC) and (b) 10:00(UTC) on 5 April 2005.

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