

A Coupled MM5-CMAQ Modeling System for Assessing Effects of Restriction Measures on PM₁₀ Pollution in Olympic City of Beijing, China

Y. Zhou¹, S. Y. Cheng^{1,*}, L. Liu^{2,*}, and D. S. Chen¹

¹College of Environmental & Energy Engineering, Beijing University of Technology, Beijing 100022, China

²Department of Civil and Resource Engineering, Dalhousie University, Halifax, NS B3J 1Z1, Canada

Received 14 August 2011; revised 25 March 2012; accepted 12 April 2012; published online 22 June 2012

ABSTRACT. In this paper, a coupled MM5–CMAQ modeling system was employed to investigate the PM₁₀ pollution issue in Beijing, China, with a focus on assessing the effects of different restriction policies implemented during and after the 2008 Olympic Games. The simulations under designed scenarios were implemented over a 2-level nested grid domain for comparing the difference of PM₁₀ concentrations under restriction and no-restrictions situations. The restriction measures include alternate-day vehicle driving, construction activities, trans-boundary emissions from neighboring provinces, and vehicle restrictions during the post-Olympic period. Meteorological contributions to the air quality improvement were also examined. The results show that significant improvement of air quality in Beijing during the 2008 Games was attributed largely to these restriction measures, although favorable weather conditions play an important role. Also, during the post-Olympic period, daily vehicle restrictions implemented temporarily under extreme weather conditions played a crucial role in alleviating Beijing’s air pollution. Beijing not only needs to take continuing efforts to address its own PM₁₀ problem, but also has a clear self-interest in demanding better environmental performance from neighboring provinces. It is suggested that Beijing would work collectively with neighboring provinces to develop a long-term multi-region initiative and strategy aimed at emission reduction for providing the citizens in this region a healthy and clean air in the long run.

Keywords: air quality, CMAQ, MM5, PM₁₀ pollution, simulation modeling

1. Introduction

Beijing was the host city of the 2008 Summer Olympic Games which took place from August 8 to August 24, 2008. Despite various concerns and controversies over this event beforehand, this Olympics have been well received by the world and have been applauded by spectators and international presses as a grand, spectacular, spellbinding, and unprecedented success. Among various concerns and fears, air pollution of Beijing has long been raised due to its potential risk to athletes' health and a potential setback to their performance in the games. The growing air pollution in Beijing comes from two fundamental facts: (1) Beijing is suited and surrounded by mountains that could easily trap smog and air pollutants; (2) rapid industrialization and urbanization took place in the past 30 years have seen dramatic increase of fume emissions from the factories, vehicles, constructions and coal-fired boilers and power plants in the city as well as the neighboring provinces. Since the successful bid of 2008 Olympics in 2001, massive efforts have been taken by the Chinese Go-

vernment including a total of over US\$20 billion investment for Beijing’s air pollution control, and this was the largest scale atmospheric pollution experiment ever conducted in Beijing. A variety of policy restrictions and incentives and technical measures, in either a permanent or temporary fashion, have been put into place. Examples of these permanent measures consist of relocation and closure of heavily polluting factories, replacement of coal by cleaner nature gas for heating boilers and power plants, suspension and removal of taxis and buses which don’t meet emission standards from the roads, and placement of more natural-gas-fueled taxis and buses in the transportation system. By the end of 2007, over 200 factories and enterprises have been relocated to the edge of city or completely shut down; 60,000 outdated taxis and buses have been suspended and removed from the roads; Beijing used 4.7 billion cubic meters in 2007 comparing to only 300 million cubic meters of natural-gas usage in 1998.

Beside these permanent measures which have been implemented for years, in July 2008 right prior to the start of the Games, stricter measures were introduced for being implemented during the July to August stretch, including (1) production and operations of more factories and coal-fired power plants were suspended and shut down temporarily; (2) passenger vehicle were restricted on the road on alternate days depending on the odd or even terminal digit of the car's license plate, which took 45% of Beijing's 3.3 million cars off the streets; (3) neighboring provinces of Tianjin, Hebei, Shanxi,

* Corresponding author. Tel.: +86 10 67391656; fax: +86 10 67391983.
E-mail address: chengsy@bjut.edu.cn (S. Y. Cheng); lei.liu@dal.ca (L. Liu).

Shandong, and Inner Mongolia were requested to close their major polluters and removing high-emission cars from roads.

With all these measures being in effect plus favorable weather conditions during the Games, the panic over pollution has finally subsided soon after the Opening Ceremony, Beijing has finally found a break and relief from its severe air pollution. Air quality recorded the API (Air Pollution Index) scores under 100 throughout the Games which was the official target. Of the 16 days of the Games, 10 days recorded an API reading from 1 to 50, and 6 days recorded an API reading from 51 to 100. According to Beijing Organizing Committee of the XXIX Olympic Games (BOCOG, 2008), the total emissions of CO, SO₂, NO₂ and PM₁₀ in 2008 have been decreased by 68.6, 51.5, 28.6, and 36.6%, respectively, compared to their emissions in 2000.

After witnessing the success of these measures, Beijing authority has pledged to continue some of them after the. However, it is yet clear for some measures in terms of their fates, and particularly their long-term effects on Beijing's air quality. For these permanent measures, the authorities want to know to what extent they will continue to play in improving Beijing's air quality, and what other permanent measures might be available for implementation; for these temporary measures, some of them will come to cease, and others might be considered for permanent enforcement. Many industrial sectors in Beijing and neighboring provinces have lost revenues due to the temporary factory shutdown and operation suspension. After the Olympics, these factories have resumed their production and operation to their full scales immediately, and a dramatic increase of fume re-emission into the air was with one's expectation. A thorough examination of these concerns and questions is more than desired.

In this study, the MM5 mesoscale meteorological model and Model-3/CMAQ model are incorporated into a general modeling system to address these questions and assess the effect of some emission control measures on Beijing's air quality in the post-Olympic period. Previous studies indicate that an integrated MM5-CMAQ modeling framework offers an effective tool to assess PM₁₀ pollution in Beijing (Cheng et al., 2007; Li et al., 2010; Wang et al., 2010). The proposed method was used to quantify the contributions of local emission sources to PM₁₀ pollution after these temporary restrictions on local sources were terminated to use, i.e., construction resumed, factory operation resumed, and vehicles unbanned. August and September 2008 were selected as the target months to represent during-Olympic periods, and October/November/December of 2008 for the post-Olympic periods. Also, two PM₁₀ pollution episodes occurred during November 2 ~ 6, 2005 and December 25 ~ 29, 2007 were chosen for comparison purposes. The models simulated the influences of different local resumed emission sources on the deterioration of Beijing's air quality in the chosen target months. Extremely adverse weather conditions were also considered for situations that weather contributed little to the dispersion of air pollutants. The simulated results could provide the governments scientific bases to make sound decision with respect to these temporary air pollution control measures.

2. Coupled MM5-CMAQ Air Quality Modeling Approach

2.1. MM5-CMAQ Model Integration and Coupling

The MM5 is a limited-area, no-hydrostatic, terrain-following sigma-coordinate model designed to simulate mesoscale and regional-scale atmospheric circulation. It was developed at Penn State University and National Center for Atmospheric Research (PSU/NCAR) as a community mesoscale model in 1970s (Anthes and Warner, 1978) and has been continuously upgraded since then to its latest version (Grell et al., 1994, 2000; Chen et al., 2007). Supported by several pre-processing and post-processing programmes, the model has been widely exploited to many fields (Chen and Grell et al., 2000; Dudhia, 2001a, 2001b; Dudhia et al., 2004). The Models-3/CMAQ (Community Multiscale Air Quality Model) is the third generation of CMAQ air quality prediction tool, and it's an Eulerian-type air quality model developed by the U.S. Environmental Protection Agency (Zhang et al., 2006; Chen et al., 2008). The Model can simulate various chemical and physical processes that are important for understanding the fate and transport of atmospheric pollutants.

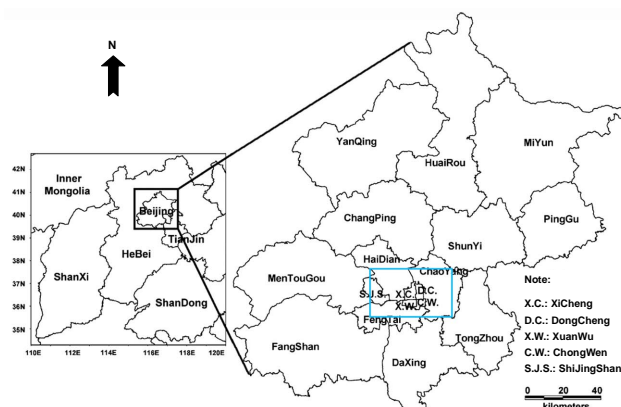


Figure 1. The 2-level nested grid domain architecture designed for the MM5-CMAQ modeling system.

In this study, the MM5 model and the Model-3/CMAQ model were coupled to simulate PM₁₀ pollution in Beijing under different control measure scenarios. The MM5 firstly provides a 4D meteorological dataset as the driving meteorological input for the CMAQ model, and its hourly output data are then processed by the Meteorology-Chemistry Interface Processor (MCIP, Version 3.3) to meet the CMAQ input requirement, during which the mass conservation between the MM5 and CMAQ is sustained. The required topography data is retrieved from the Digital Elevation Model from USGS with 30s spatial resolution, and the land-use data is also obtained from USGS 1km NOAA/AVHRR satellite data sets. The MM5-CMAQ modeling system requires an initial meteorological field and detailed emission data set for simulating PM₁₀ pollution. The 3D first-guess meteorological fields for MM5 simulation were obtained from the Global Tropospheric Analysis datasets provided by the US National Center for Environ-

mental Prediction, and were available every 6 hrs with $1 \times 1^\circ$ resolution. A county-level air pollutant emission inventories were obtained from Beijing Environmental Protection Bureau (EPB) and other EPBs of the neighboring provinces. The NOX emissions and anthropogenic non-methane volatile organic compounds (NMVOC) emissions from the neighboring provinces were taken from the emission inventories prepared by Streets et al. (2003). The biogenic VOCs emission was obtained from Global Emission Inventory Activity (GEIA) (Benkovitz et al., 1995). These emission inventories were processed by the modified Sparse Matrix Operator Kernel Emissions Modeling System (SMOKE) (Houyoux and Vukovich, 1999). The emission preprocessor SMOKE linked each emission inventory dataset to generate high spatial and temporal resolution emission inputs required by CMAQ.

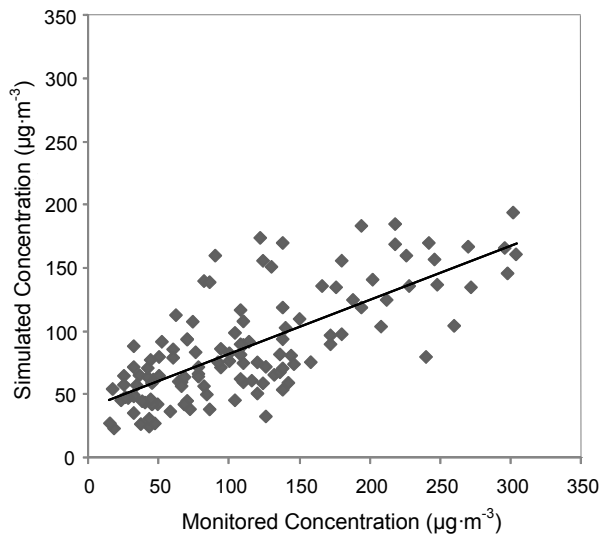


Figure 2. The scatter plots of simulated versus observed PM₁₀ concentration for the target months in 2008.

2.2. MM5-CMAQ Simulation Domain Design and Evaluation Grid Cell Selection

The coupled modeling system was run in a 2-level nested grid domain, as shown in Figure 1. The domain was designed based on a Lambert map projection centered at (39° N, 114° E). Horizontally, the outer domain has a spatial resolution of 12×12 km and consists of 70×76 grid cells. Its coverage includes Beijing municipality and most areas of neighboring provinces. The inner domain covers Beijing municipality only with a spatial resolution of 4×4 km and contains 49×49 grid cells. The simulation domain designed for the MM5 has 5 more grids than the CMAQ in each direction in order to minimize the side effect at the boundary of the meteorological model. Vertically, the MM5 meteorological circulation was simulated on 23 vertical layers. The 23 layers were incorporated into the sigma coordinate with varying thickness and lower air has denser layers for better providing specific planetary boundary information. The 23 layers were merged into 12 layers vertically by the MCIP module before using the CMAQ for

PM₁₀ simulation in both outer and inner domains.

In this study, 24 evaluation grid cells (EGC) were chosen from the inner grid domain and used for air quality simulation under different emission control scenarios (Figure 1). The mean PM₁₀ concentration of each EGC was calculated through running the MM5-CMAQ system. The arithmetic average of the simulated mean PM₁₀ concentrations for all 24 EGCs was then calculated to approximate the average PM₁₀ concentration of Beijing.

3. Emission Reduction Control Measures

Based on the control measures implemented prior to and during the Games, four different PM₁₀ emission reduction scenarios were designed as follows and their effects on Beijing’s air quality were examined. The approaches used for calculating the emission reduction under each scenario were also discussed.

Measure #1: Vehicle Alternate-Day Driving Restriction

This restriction refers to a traffic control measure that vehicles and motorists will be limited to be driving on roads on alternate days, based on the last digit on their license plate (odd or even number). Categories of vehicles to be restricted include private passenger vehicles, all-level duty trucks and motorcycles. Police cars, fire trucks, ambulances, and other municipal service vehicles such as taxis, public transit, and licensed vehicles are excluded from the restriction list. The reduction of vehicle exhaust emissions can be calculated by:

$$Q_{PM_{10}}^- = \sum_i P_i \times \eta_i^- \times EF_i \times M_i \tag{1}$$

Where $Q_{PM_{10}}^-$ is the emission reduction (tons) of PM₁₀; P_i is the total number of vehicles in category i ; η_i^- is ratio of vehicle in category i which is banned on the road under the alternate-day restriction policy, and in this study the value of η_i^- approximately equals 50%; EF_i is the emission factor (g/km) of vehicles in category i for PM₁₀ (Tsinghua University, 2009); M_i is the average annual mileage (km) for vehicles in category i (Liu et al., 2005; Che et al., 2009).

Alternate-day driving restrictions could lead to not only the reduction of vehicle exhaust emissions, but also the reduction of road fugitive dust (mainly PM₁₀). Road fugitive dust reduction can be calculated by:

$$Q_{PM_{10}}^- = \sum_i Q_i \times r_i \tag{2}$$

where $Q_{PM_{10}}^-$ is the emission reduction (tons) of road fugitive dust in terms of PM₁₀; Q_i is PM₁₀ emission (tons) from road category i ; r_i is the ratio of decreased dust fall on road category i due to the alternate-day driving ban. With the traffic be restricted to a certain extent, road dust emissions (falling

and depositing on) the ring road and arterial road can be reduced by 67 and 60%, respectively (Tian et al., 2009).

Measure #2: Restrictions on Infrastructure Constructions

Restrictions on all major construction activities within Beijing municipality were placed during the 2008 Games. The construction dusts can be categorized as in-place operation dust, road dust, and wind-erosion dust. The reduction of dust emissions from different construction dust categories can be calculated by:

$$Q_{\text{PM}_{10}}^- = \sum_i Q_i \times r_i \quad (3)$$

where $Q_{\text{PM}_{10}}^-$ is the emission reduction (tons) of PM_{10} ; Q_i is dust emission (tons) from construction dust category i ; r_i is the ratio of decreased emission of PM_{10} from construction dust category i due to the restriction measure. During the Games, all the construction earthworks in Beijing were suspended, and emissions of in-place construction dust and road dust were close to zero (thus $r = 100\%$); wind-erosion dust emission was reduced by 80% by the site-coverage measure (thus $r = 80\%$) (Tsinghua University, 2009).

Measure #3: Restrictions on Emission from Neighboring Provinces of Beijing

During the Games, Tianjin and Hebei were also requested to place similar temporary restrictions on their major pollutants and high-emission cars. The emission reductions from vehicle exhaust, road fugitive dust and construction dust can be calculated using Equations (1), (2) and (3). The industrial emission reduction ratio was set to be 30% according to BJEPB (2008).

Measure #4: Vehicle Restrictions during the Post-Olympic Period

After the Games were over, another two major vehicle restriction measures have been implemented in Beijing: (1) 30% of government passenger vehicles were restricted to be driving on the road, (2) private passenger vehicles were restricted off the road based on a newly designed last-digit plate number system, and as a result the motorists have to be off the road once a week. The vehicle emission reduction due to this new rule can also be calculated by Equation (1).

In this study, two general simulation scenarios were considered: Zero Emission Reduction Scenario (ZERS) and Different-Level Emission Reduction Scenarios (DLERSs), and they were run for the target period from August 1 to September 20 in 2008. The ZERS refers to the situation which the PM_{10} concentration is simulated with the participation of the entire county-level air pollutant emission inventories from Beijing and neighboring provinces, and the results represent the worst PM_{10} pollution situation in Beijing under zero reduction. The DLERSs refer to the situations which the PM_{10} concentration is simulated under different emission reduction levels

from different sources. Therefore, shares of contributions from different sources can be computed. Meanwhile, with different restriction measures being effective, a new set of PM_{10} concentrations and contribution shares from different reduced sources can also be calculated. The concentration differences represent the impact of different control measures on the air quality of Beijing.

4. Results and Discussion

4.1. MM5-CMAQ Model Performance Test

The coupled MM5-CMAQ modeling system was tested first to evaluate its performance before it was applied to run the designed simulation scenarios. The performance test was conducted by the statistical scatter plot diagram. Data from seven monitoring stations were used plotting pairs of simulated versus monitored PM_{10} concentrations on an x-y ordinate. Figure 2 presents the scatter plot for January, April, August and October in 2008. Pearson correlation is found to be 0.7, indicating an acceptable model performance.

4.2. Effect of Weather Conditions on PM_{10} Concentration during the Games

We chose both periods of August 1 to September 20 in 2006 and 2008 as the target period for investigating the meteorological effects. The simulated mean hourly PM_{10} concentrations for both periods were firstly converted to the mean daily values and then compared to each other. The simulation results indicated that the weather conditions caused a decrease of mean monthly PM_{10} concentration by 11.7% in August 2008 and an increase by 4.1% in September 2008 when compared to the results of 2006. However, according to the field monitoring data, the mean monthly concentration of PM_{10} in 2008 was reduced by 29.3% in August and by 51.2% in September comparing to 2006. It can be concluded that although favorable weather conditions did help improve the air quality in Beijing during the Olympics, the role it played was quite minor.

4.3. Effects of Restriction Measures on PM_{10} Concentration during the Games

4.3.1. PM_{10} Contributions from Different Sources without Implementing Restrictions

In order to examine the effects of the restriction measures, PM_{10} contributions from existing emission sources without implementing these restrictions should be investigated, and four sub-scenarios were designed and run for this purpose, including 0-Emission-Reduction Scenario (S0), 0-Beijing-Emission Scenario (S1), 0-Beijing-Vehicle-Emission Scenario (S2), 0-Beijing-Road-Dust-Emission Scenario (S3), and 0-Beijing-Construction-Dust-Emissions Scenario (S4). August 1 to September 20 of 2008 was chosen as the target period for the simulations. Based on the simulated mean hourly PM_{10} concentration for the target period, the contribution ratio (CR) of each emission source to PM_{10} in Beijing was calculated, and the hourly CR was then converted to the mean daily CR. It was

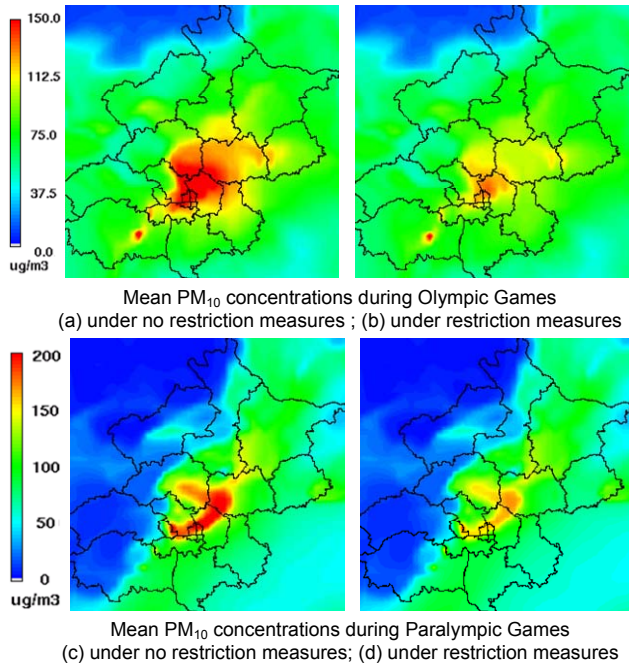
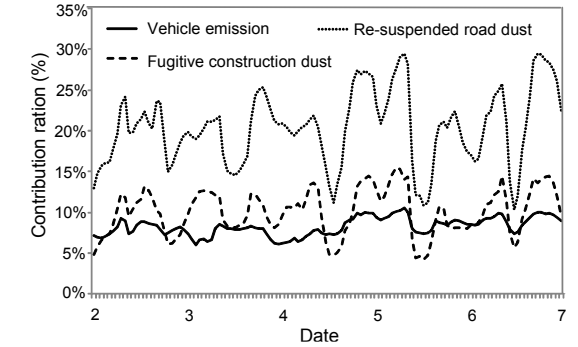


Figure 3. Simulated average PM₁₀ concentrations during the Olympic Games and Paralympic Games under different scenarios.

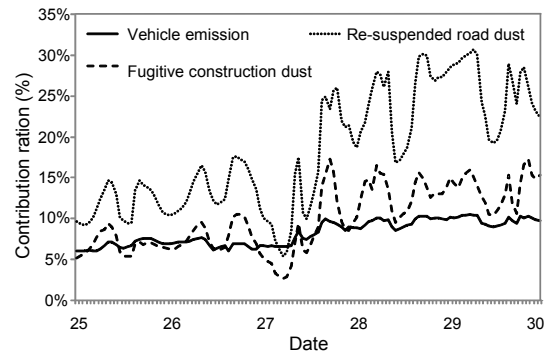
found that three local PM₁₀ emission sources (i.e., vehicle, road dust and construction) contribute collectively to PM₁₀ pollution in Beijing with a CR of 44.1 and 45.3% for August and September, respectively. The mean monthly contribution ratios from neighboring provinces were 34.7% in August and 32.4% in September. It should also be noted that total contribution proportion from all 4 sources has exceeded 70%. This indicates that proper restriction measures on local dominant sources and neighboring sources have to be taken for improving Beijing's air quality.

4.3.2. Effects of Temporary Restriction Measures on PM₁₀ Pollution during the Games

Effects of restriction measures on improving PM₁₀ pollution were investigated through the following scenarios: 0-Emission-Reduction Scenario (S0), Alternate-Day-Vehicle-Restriction Scenario (S5), Earthwork-Construction-Site-Restriction Scenario (S6), and Neighboring-Province-Restriction Scenario (S7). The simulation target period was kept same. The simulated PM₁₀ concentrations under each designed scenario were compared to the field data observed during the Games as well as to the simulated PM₁₀ concentrations without implementing the restriction measures. Thus, the effects of restriction measures on the air quality can be assessed and quantified. It was found that PM₁₀ concentration was increased by an average of 28.6% in August and an average of 27.9% in September if no restriction measures were put into effect; the average increase of PM₁₀ concentration in August was 20.58 and 19.13 μg/m³ in September. If that was the case, PM₁₀ concentration of Beijing during Games would exceeded National Air Quality Standard Grade II level. The average PM₁₀



(a) PM₁₀ pollution episode occurred during November 2 - 6, 2005



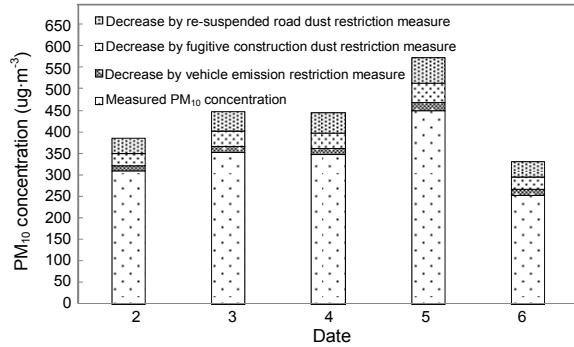
(b) PM₁₀ pollution episode occurred during December 25 - 29, 2007

Figure 4. Simulated hourly PM₁₀ contribution ratios from different emission sources during the 2 historical pollution episodes.

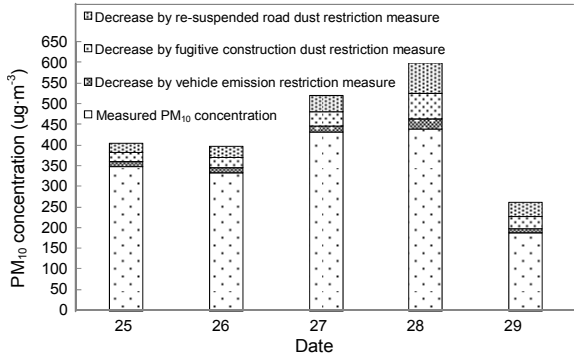
concentrations during the Olympic Games and Paralympic Games are depicted in Figure 3(a-d). It is indicated that these restriction measures implemented during the Games were effective and played a significant role in improving the air quality of Beijing.

4.3.3. Effects of the Post-Olympic Private Vehicle Restriction Measure on Beijing's Air

The temporary restriction measures implemented during the Games were proved to be very effective; logically, the municipal authorities pledged to continue some of the restrictions for improving air quality in the long run. A last-digit plate number system was then newly designed to restrict private passenger vehicles from the road on an in-turn daily basis, and under this rule the motorists have to stop driving their vehicles once a week depending on the last digit of their license plate number. This new vehicle restriction rule was tried to implement in Beijing from October 11, 2008 to April 10, 2009. It was estimated that about 0.8 million automobiles were restricted to be driving on road every day, leading to a reduced PM₁₀ emission collectively from direct vehicle exhaust emission and indirect road dust emission. In order to assess the effect of this new restriction measure on post-Olympic Beijing, 2 simulation scenarios were designed: 0-Emission-Reduction Scenario (S0) and Daily-Vehicle-Restriction Scenario (S8). The simulation results show that, without implementing this new restriction rule, the increasing ratios of mean monthly PM₁₀

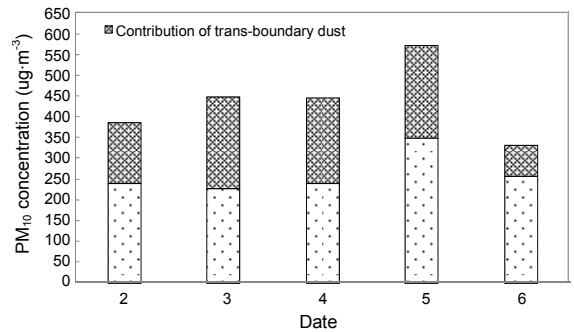


(a) PM₁₀ pollution episode occurred during November 2 - 6, 2005

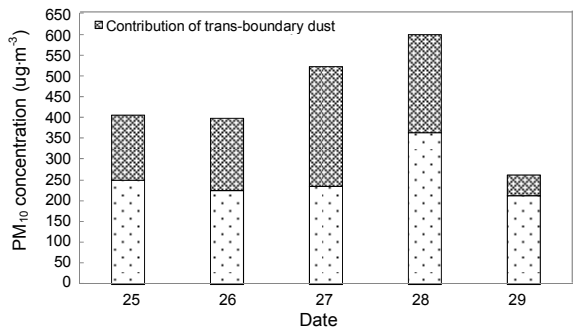


(b) PM₁₀ pollution episode occurred during December 25 - 29, 2007

Figure 5. Simulated daily PM₁₀ concentration and its decreases by 3 temporary measures during 2 historical PM₁₀ pollution episodes.



(a) PM₁₀ pollution episode occurred during November 2 - 6, 2005



(b) PM₁₀ pollution episode occurred during December 25 - 29, 2007

Figure 6. Daily PM₁₀ concentrations contributed from neighboring provinces of Beijing during the 2 pollution episodes.

concentration were 6.81, 8.27, and 7.85% in October, November, and December of 2008, respectively. The mean monthly PM₁₀ concentration had an increase of 6.88 $\mu\text{g}/\text{m}^3$ in October, 9.68 $\mu\text{g}/\text{m}^3$ in November and 12.10 $\mu\text{g}/\text{m}^3$ in December. It is apparent that this restriction measure could help improve Beijing's air quality to a certain but limited extent; however, although the contribution was limited, it was believed that this measure will still be playing an important role, particularly considering the circumstances that other temporary restriction measures had ceased to use and Beijing was facing an immediate pressure of air quality re-deterioration. On its negative side, this measure has brought certain inconvenience to the motorists and relevant sectors. Therefore, additional studies might be needed to examine in what form this measure can bring more benefits to Beijing.

4.3.4. Effects of Temporary Measures Implemented on Extreme Weather Days

Due to the positive effects produced by the temporary restriction measures, it has been in discussion since the closure of the Olympic Games that some of these restrictions can be considered to implement on some extreme weather days to alleviate the worsen air pollution possibly caused by bad weather conditions (daily average PM₁₀ concentration exceeds 250 $\mu\text{g}/\text{m}^3$). Those temporary measures could be alternate-day vehicle restriction, all construction suspension, and more street cleanups. In this study, the coupled modeling system was employed to simulate two historical pollution episodes occurred during November 2 ~ 6, 2005 and December 25 ~ 29, 2007, respectively, for assessing the effects of temporary control measures on PM₁₀ pollution when the weather conditions are extremely unfavorable for pollutant dispersion and transport. Figure 4 plots the simulated ratio curves of hourly PM₁₀ concentrations contributed from vehicle emission, road dust and fugitive construction dust during the 2 selected episodes. Figure 5 shows the simulated daily PM₁₀ concentrations during both pollution episodes, and as a comparison, the decreases of PM₁₀ concentrations if the 3 temporary measures are to be implemented. It is calculated that PM₁₀ concentration was decreased by an average of 21.56% in November episode and an average of 20.30% in December episode with temporary measures being implemented. The average decrease of PM₁₀ concentration in November episode was 93.8 $\mu\text{g}/\text{m}^3$ and was 88.4 $\mu\text{g}/\text{m}^3$ in December episode. The placement of temporary restriction measures under extremely adverse weather conditions has an apparent positive impact on Beijing's air quality.

In this study, we also did the simulation trials in terms of limiting emissions from neighboring provinces for pursuing a better air quality in Beijing. The results show that the average contribution ratios from neighboring provinces were 39.15% in November episode and 39.26% in December episode. Figure 6 presents the daily PM₁₀ concentration contributed from neighboring provinces of Beijing during both pollution episodes. The results show that Beijing's air pollution issue is attributed not only from its own internal emission sources, but also from the sources outside Beijing. Therefore, Beijing not only needs to take continuing efforts to addresses its own

PM₁₀ problems, but also has a clear self-interest in demanding better environmental performance from neighboring provinces. Beijing should be more active in developing a long-term collective multi-region stipulations and initiatives aimed at emission reduction through enhanced management, technological innovation and societal life-style changes, in order to keep improving Beijing's air quality in the long run.

5. Conclusions

In this study, the MM5 and Model-3/CMAQ models were coupled to investigate the effects of different control measures implemented around the Olympic periods on Beijing's PM₁₀ pollution issue. The simulations under a variety of designed scenarios were implemented over the 2-level nested grid Beijing domain. The modeling results indicate that significant improvement of air quality in Beijing during the 2008 Games was attributed largely to the restriction measures taken by both Beijing and neighboring provinces, although favorable weather conditions play an important role in helping improve the air quality. The modeling results also show that, during the post-Olympic period, daily vehicle restriction plays a crucial role in alleviating air pollution although the contribution was limited. However, it was believed that this measure will still be very important, particularly considering the circumstances that other temporary restriction measures had ceased to use and Beijing was facing an immediate pressure of air quality re-deterioration. PM₁₀ concentration in two historical pollution episodes (November 2 ~ 9, 2005 and December 25 ~ 29, 2007) would decrease by one fifth if the traffic and construction bans were placed temporarily during the unfavorable weather conditions. The modeling results also indicate that PM₁₀ trans-boundary contribution ratios from neighboring provinces during the two episodes were quiet significant. It is evident that Beijing's air pollution issue is attributed not only from its own internal emission sources, but also from the sources outside Beijing. Beijing need to work collectively with neighboring provinces to develop a long-term multi-region initiative and strategy for best interests of Beijing's citizens in terms of a clear sky and a clean air in the long run.

Acknowledgments. This paper was supported by the "Beijing Science and Technology Project" (No. D09040903670801) of the Beijing Municipal Science & Technology Commission as well as the Ministry of Environmental Protection Special Funds for Scientific Research on Public Causes (No. 200909008). The authors would like to thank the Natural Sciences Foundation of China (No. 51038001 & 50878006), Natural Science Foundation of Beijing (No. 8092004 and No. 8082022), Beijing NOVA Program of China (No. 2009B07), Innovation Team Project of Beijing Municipal Education Commission (PHR201007105) as well as the Cultivation Fund of the Key Scientific and Technical Innovation Project, Ministry of Education of China (No. 708017) for supporting this work. The authors are grateful to the editors and the anonymous reviewers for their insightful comments.

References

Anthes, R. A., and Warner, T. T. (1978). Development of hydrodynamic models suitable for air pollution and other mesometeorological studies. *Mon. Weather Rev.*, 106(8), 1045-1078. [http://dx.doi.org/10.1175/1520-0493\(1978\)106<1045:DOHMSF>2.0.CO;2](http://dx.doi.org/10.1175/1520-0493(1978)106<1045:DOHMSF>2.0.CO;2)

- Beijing Environmental Protection Bureau (BJEPB), 2008. Beijing air quality improved by 60% during the Olympic Games. http://news.xinhuanet.com/politics/2008-09/22/content_10088747.htm
- Beijing Organizing Committee for the Games of the XXIX Olympic Games (BOCOG), 2008. Beijing air quality. <http://en.beijing2008.cn/live/pressconference/mpc/n214514906.shtml>.
- Benkovitz, C. M., Berdowski, J. J. M., and Veldt, C. (1995). The GEIA global gridded inventory of anthropogenic VOCs. In: The Emission Inventory: Applications and improvement, Raleigh, *Air Waste Manage.*, Pittsburgh, PA, 609-618.
- Che, W. W., Zheng, J. Y., and Zhong, L. J. (2009). Vehicle exhaust emission characteristics and contributions in the Pearl River Delta Region. *Res. Environ. Sci.*, 22, 456-461 (in Chinese).
- Chen, D. S., Cheng, S. Y., Liu, L., Chen, T., and Guo, X. R. (2007). An integrated MM5-CMAQ modeling approach for assessing trans-boundary PM₁₀ contribution to the host city of 2008 Olympic Summer Games in Beijing, China. *Atmos. Environ.*, 41(6), 1237-1250. <http://dx.doi.org/10.1016/j.atmosenv.2006.09.045>
- Chen, D. S., Cheng, S. Y., Liu, L., Lei, T., Guo, X. R., and Zhao, X. Y. (2008). Assessment of the integrated ARPS-CMAQ modeling system through simulating PM₁₀ concentration in Beijing, China. *Environ. Eng. Sci.*, 25(2), 191-205. <http://dx.doi.org/10.1089/ees.2006.0166>
- Chen, F., and Dudhia, J. (2001a). Coupling an advanced land-surface/hydrology model with the Penn State/NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Mon. Weather Rev.*, 129(4), 569-585. [http://dx.doi.org/10.1175/1520-0493\(2001\)129<0569:CAALSH>2.0.CO;2](http://dx.doi.org/10.1175/1520-0493(2001)129<0569:CAALSH>2.0.CO;2)
- Chen, F., and Dudhia, J. (2001b). Coupling an advanced land-surface/hydrology model with the Penn State/NCAR MM5 modeling system. Part II: Preliminary model validation. *Mon. Weather Rev.*, 129(4), 587-604. [http://dx.doi.org/10.1175/1520-0493\(2001\)129<0587:CAALSH>2.0.CO;2](http://dx.doi.org/10.1175/1520-0493(2001)129<0587:CAALSH>2.0.CO;2)
- Cheng, S. Y., Chen, D. S., Li, J. B., Wang H. Y., and Guo, X. R. (2007). The assessment of emission-source contributions to air quality by using a coupled MM5-ARPS-CMAQ modeling system: A case study in the Beijing metropolitan region, China. *Environ. Model. Software*, 22(11), 1601-1616. <http://dx.doi.org/10.1016/j.envsoft.2006.11.003>
- Dudhia, J., Gill, D., Manning, K., Wang, W., and Bruyere, C. (2004). PSU/NCAR mesoscale modeling system tutorial class notes and user's Guide: MM5 modeling system version 3. National Center for Atmospheric Research, USA.
- Grell, G. A., Dudhia, J., and Stauffer, D. (1994). A description of the fifth generation Penn State/NCAR mesoscale model (MM5). NCAR Technical Note, NCAR TN-398-STR.
- Grell, G. A., Emeis, S., Stockwell, W. R., Schoenemeyer, T., Forkel, R., Michalakes, J., Knoche, R., and Seidl, W. (2000). Application of the multiscale, integrated MM5/chemistry model to the complex terrain of the VOTALP valley campaign. *Atmos. Environ.*, 34(9), 1435-1453. [http://dx.doi.org/10.1016/S1352-2310\(99\)00402-1](http://dx.doi.org/10.1016/S1352-2310(99)00402-1)
- Houyoux, M., and Vukovich, J. (1999). Updates to the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system and integration with Models-3, presented at The Emissions Inventory: Regional Strategies for the Future Conference. *Air Waste Manage.*, Raleigh, NC.
- Li, M. J., Chen, D. S., Cheng, S. Y., Wang, F., Li, Y., Zhou, Y., and Lang, J. L. (2010). Optimizing emission inventory for chemical transport models by using genetic algorithm. *Atmos. Environ.*, 44(32), 3926-3934. <http://dx.doi.org/10.1016/j.atmosenv.2010.07.010>
- Liu H., He C. Y., Lents, J., Davis, N., Osses, M., and Nikkila, N. (2005). Beijing vehicle activity study. *Streets, D. G., Bond, T. C., Carmichael, G. R., Fernandes, S. D., Fu,*

- Q., He, D., Klimont, Z., Nelson, S. M., Tsai, N. Y., Wang, M. Q., Woo, J. H., and Yarber, K.F. (2003). The MICS-Asia Phase II emission inventory. In: the Sixth Workshop on the Transport of Air Pollutants in Asia (Model Intercomparison Study - MICS-Asia), International Institute for Applied Systems Analysis, Laxenburg, Austria.
- Tian, G., Li G., Qin J. P., Fan, S. B., Huang, Y. H., and Nie, L. (2009). Influence of traffic restriction on road and construction fugitive dust. *Environ. Sci.*, 30, 1528-1532 (in Chinese).
- Tsinghua University. (2009). Air quality improvement theory, technology and its applications in mega city (in Chinese).
- Wang, F., Chen, D. S., Cheng, S. Y., Li, J. B., Li, M. J., and Ren, Z. H. (2010). Identification of regional atmospheric PM₁₀ transport pathways using HYSPLIT, MM5-CMAQ and synoptic pressure pattern analysis. *Environ. Model. Software*, 25(8), 927-934. <http://dx.doi.org/10.1016/j.envsoft.2010.02.004>
- Zhang, M., Pu, Y., Zhang, R., and Han, Z. (2006). Simulation of sulfur transport and transformation in East Asia with a comprehensive chemical transport model. *Environ. Model. Software*, 21(6), 812-820. <http://dx.doi.org/10.1016/j.envsoft.2005.02.008>