

Simulation on SO₂ and NO_x Emission from Coal-Fired Power Plants in North-Eastern North America

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Abstract

MM5-SMOKE-CMAQ regional air quality modeling system was used to simulate pollutants emission from coal-fired power plants in North-Eastern North America. The effects of SO₂ and NO_x on air quality producing from coal-fired power plants in the summer of 2001 were analyzed. Simulations show the contributions of SO₂ and NO_x emission from coal-fired power plants using different scenarios, coal-fired power plants from US and Canada contribute 67.2% and 32.8% for total SO₂ concentration, 17.6% and 6.0% for total NO_x concentration in researched domain. Some control measures for coal-fired power plants were discussed. Further controls for the emissions of SO₂ and NO_x from coal-fired power plants are necessary to reduce the adverse environmental effects.

Keywords: Electric Generating units, CMAQ, Air Quality, Pollutants Control

1. Introduction

There is a long history of public concern about the emission of SO₂ and NO_x, these emissions contribute to acid deposition, ultimately leading to a wide range of environmental impacts, including damage to forests and soils, fish and other living things, materials, and human health. as well as the formation of fine particles and gases that can impair visibility. SO₂ and NO_x all are the precursors of acid rain [1]. Coal-fired power plants are regarded globally as the major contributor to local air quality degradation and to global environmental impacts such as acid rain and greenhouse phenomenon [2]. In the United States, over 70 percent of this electricity was produced through the combustion of fossil fuels, primarily coal and natural gas, while 26 percent of this generation was produced from fossil fuels in Canada.

Legislation enacted for control the emission of these two pollutants during the past two decades. In the Clean Air Act Amendments (CAAA) of 1990, US Environmental Protection Agency (EPA) has promulgated several regulations and proposed rules to decrease these adverse effects by reducing the emissions of SO₂ and NO_x from coal-fired power plants. Since Congress passed the Clean Air Act (CAA), power plants have cut emissions of SO₂ and NO_x dramatically [3,4]. Many of these reductions have been achieved by conversion to lower-sulfur fossil fuels, primarily natural gas, with attendant

increases in costs. An alternative to conversion is to use mitigation technologies to reduce the emissions. The most common such technologies are reducing fuel sulfur levels and filtering emissions using flue gas desulfurization (FGD) and denitrification systems [5,6].

Analyses of the environmental effects arising from power plants using a variety of models [7-10] suggest that air quality effects depend on a wide variety of local atmospheric parameters as well as on the combustion technology. In some cases [11], regional transport dominates local sources during pollution episodes, while in other cases [12], transport is strongly affected by local topology. In view of this variable sensitivity, the effects of thermal power generation on air quality should be assessed on a case by case basis for well defined geographical locations and time periods. Plumes from power plants in certain locations have been implicated in significantly reduced air quality [13,14].

In this study, we use regional atmospheric modeling to explore the air quality implications of coal-fired power plants in North-Eastern North America. We design different scenarios to study the contributions of coal-fired power plants from United States and Canada. The concerned pollutants are SO₂ and NO_x, which all are the leading precursors of acid rain; they have large environmental influences on the acid sensitive regions of North-Eastern North America. Research results can be made references for pursuing further emission reductions in US and Canada.

2. Modeling Description

EPA's Models-3/Community Multi-scale Air Quality (CMAQ) [15] modeling system is a numerical transport and chemical model which is developed by US EPA and is implemented in a full modular approach. It means that the user can select different chemical schemes (CBM-IV, V, SAPRAC-99, RADM, etc.) and different numerical schemes. It has different capabilities such as: Process analysis, IRR analysis, etc.). It can handle interactions at different dynamic scales and among multi-pollutants with one modeling system. In this research, CMAQ (v4.5) is employed to simulate SO₂ and NO_x for the summer season of 2001 (May 1 through September 1). The model uses the Carbon Bond 4 (CB4) gas phase chemical mechanism with 2005 updates to extend the inorganic reactions [16].

2001 national emissions inventories was used and processed by the Sparse Matrix Operator Kernel Emissions Modeling System (SMOKE, v2.2) [17]. SMOKE system provides an efficient tool for converting emissions inventory data into the formatted emissions files: gridded, temporalized and speciated, which are required by CMAQ. Area sources, non-road sources, mobile emissions, biogenic emissions and point sources are treated separately and merged.

Meteorological input data for the modeling runs are processed using the National Center for Atmospheric Research (NCAR) 5th generation Mesoscale Model (MM5, v3.0) [18,19]. Important MM5 parameterizations and physics options apply to each summer include mixed phase microphysics, planetary boundary layer (PBL), and the land surface module. Meteorology-Chemistry Interface Processor (MCIP, v2.0) is used to process the MM5 output fields and generate the meteorological parameter fields required by SMOKE and CMAQ as well as the dry deposition velocity fields of chemical species required by CMAQ.

The model, as applied here, uses a horizontal resolution of $36 \times 36 \text{ km}^2$, with 23 layers in the vertical. The model domain covers most Eastern of America in order to minimize the effects of boundary conditions on model results. Additional model simulation was performed over an embedded domain covering the North-Eastern North America including the Great Lakes, with a grid spacing of 12 km. Modeling coarse domain and 2-way nested 12km domain are shown in **Figure 1**.

We explore the effects of the three emission scenarios described below:

- 1) Scenario 1 (Base case): All emissions in the 2001 criteria inventories were used.
- 2) Scenario 2: Coal emissions from power plants of US and Mexico removed from point source inventory, but kept the emission inventory of Canada same as Scenario 1.
- 3) Scenario 3: Coal emissions from power plants in

Canada were removed from point source inventory, but kept the emission inventories of US and Mexico same as Scenario 1.

3. Modeling Evaluation

To validate the basic calculation, we compared the values of SO₂ and NO_x produced by the model for the time period from May 1 to September 1, 2001 with the corresponding measurements from AQS air quality monitoring stations located in Domain 2.

The simulation for SO₂ and NO_x aren't very good, the model has an under-prediction for SO₂ and NO_x average concentration; Normalized Mean Bias (NMB) and Normalized Mean Error (NME) for SO₂ are -51.75% and 71.28%; for NO_x are -9.77% and 55.38% respectively. The reason that modeled deviates from observations is that measurements are made near the sources where the model emission schemes will never be able to reproduce small-scale fluctuations observed. Sub-grid scale variability in emissions will have a major impact on the comparison between the model and observation. More efforts should be done to improve the simulation for SO₂ and NO_x. Moreover, the study's conclusions are obtained mainly by subtracting the scenarios from base case, thereby reducing the effects of errors in research results.

4. Modeling Results and Analysis

4.1. SO₂ Emission and Changes Resulting from Different Scenarios

SO₂ are formed from fuel containing sulfur (mainly coal and oil) is burned at power plants and during metal smelt-

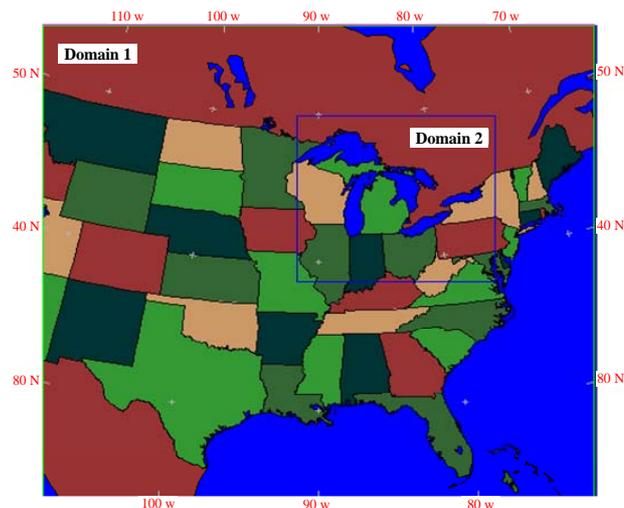


Figure 1. The set of air quality modeling domain.

ing and other industrial processes. SO₂ emissions from power plants react with other chemicals in the atmosphere to form sulfate particles, an important contributor to the fine particle mix that circulates with the air we breathe.

Figure 2 and **Figure 3** show the average SO₂ emission flux and SO₂ concentration in North-Eastern North America in the summer season of 2001. The average SO₂ emission flux was 0.021mol/s in whole domain in the summer. Several regions such as Chicago, southern Ohio, northern West Virginia and western Pennsylvania etc. were responsible for a significant proportion of SO₂ emissions. Many large coal-fired power plants encompasses in Ohio River Valley, which is a well-known emission source of precursors of acid rain in the North America. Same as emission, these areas had higher SO₂ average concentration in this summer.

Figure 4 shows the average difference of SO₂ concentration from base case and Scenario 2, which produce by

the average of SO₂ concentration simulating from base case minus those of Scenario 2. The regions of high SO₂ concentration are the areas affected by the SO₂ emission of coal-fired power plants apparently. The highest difference of SO₂ concentration exists at the region of west Pennsylvania about 0.012 ppmv, it is easy to see that the Ohio River Valley is biggest source of SO₂ from coal-fired power plants in researched domain.

Figure 5 shows the average SO₂ concentration simulating from three scenarios in the summer of 2001. The average SO₂ concentration of base case in domain 2 is 0.001 ppm in this summer. Average SO₂ concentration getting from Scenarios 2 and 3 are 0.00033 and 0.000672 ppm, these mean coal-fired power plants from US and Canada contribute 67.2% and 32.8% for total SO₂ concentration in researched domain.

According to EPA report, power plants account for 69% of total SO₂ emission in the US in 2001 [20]. So, this is consistent with our research results for the most part.

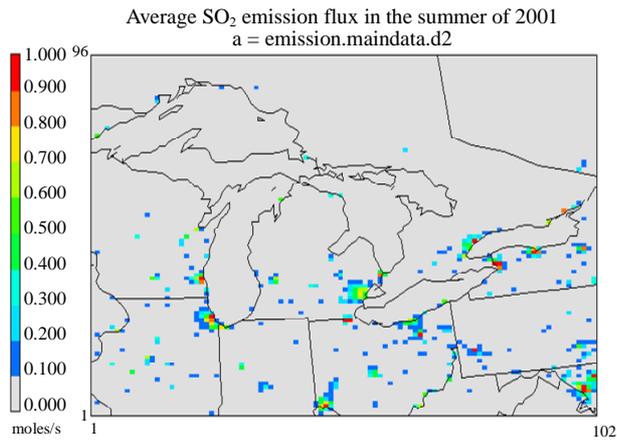


Figure 2. Average SO₂ emission flux in the summer season of 2001 in North-Eastern North America.

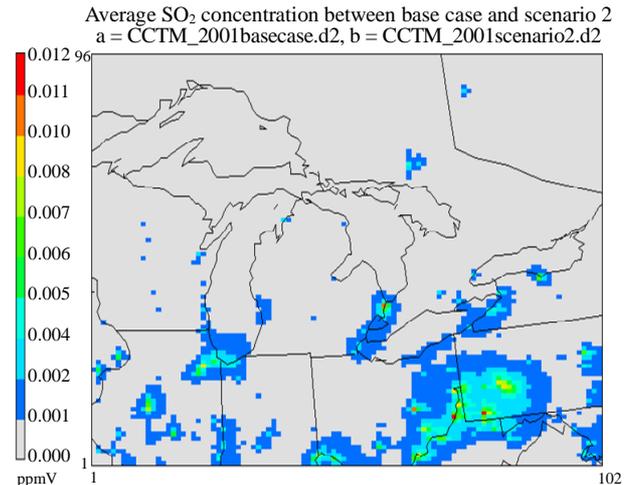


Figure 4. Spatially resolved hourly average difference of SO₂ concentration from base case and Scenario 2 in the summer season of 2001 in North-Eastern North America.

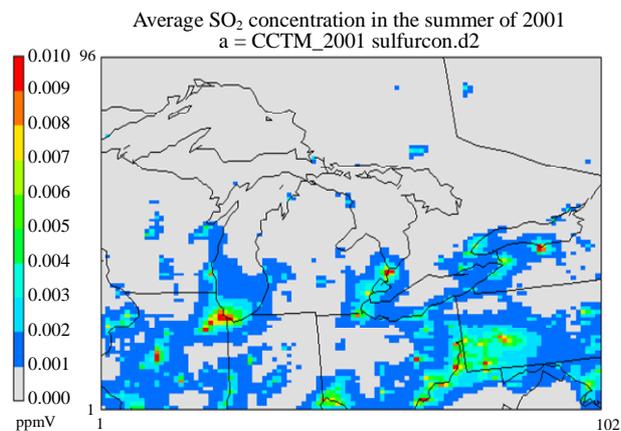


Figure 3. Spatially resolved hourly Average SO₂ concentration in the summer season of 2001 in North-Eastern North America.

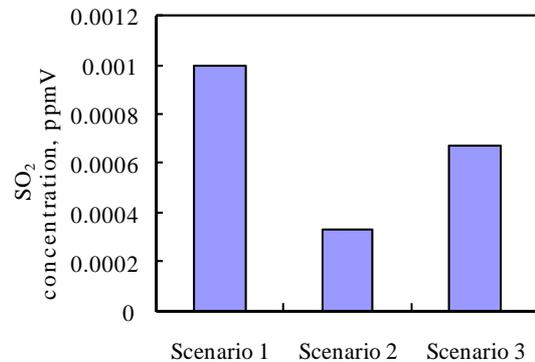


Figure 5. Average SO₂ concentration simulating from different scenarios in the summer of 2001.

4.2. SO₂ Emission Control from Coal-Fired Power Plants

To help reduce acid rain, EPA is implementing a program to reduce releases of SO₂ and other pollutants from coal-fired power plants. The first phase began in 1995 for SO₂ and targets the largest and highest emitting power plants. The second phase (started in 2000) sets tighter restrictions on smaller coal-, gas-, and oil-fired plants. This program will reduce annual SO₂ emissions by 10 million tons (almost half the 1980 level) between 1980 and 2010. The control of SO₂ emissions is currently achieved using an innovative strategy called cap and trade, established by the CAAA of 1990 and administered by EPA, which is the world's first large-scale cap-and-trade program for air pollution. The program is designed to reduce electric power sector emissions of SO₂ through a national, market-based cap-and-trade system for SO₂ emissions with the goal of reducing the adverse effects of acid rain. The total SO₂ release allowed is set at a maximum of 8.95 million tons by the year 2010—approximately half of 1980 emissions [21].

Four main technology strategies for SO₂ emissions control have been used by the electricity industry [22]:

- 1) Tall gas stacks that disperse emissions away from immediate areas;
- 2) Intermittent controls which involve routine operational adjustments to reduce power plant SO₂ emissions in response to atmospheric conditions;
- 3) Pre-combustion reduction of sulfur from fuels; and
- 4) Removal of SO₂ from the post-combustion gas stream, the main method is FGD. There are a wide variety of FGD techniques, of which the most common are wet scrubbers. Wet scrubbers work by using a slurry or solution to absorb SO₂, producing an initially wet by-product. Frequently, limestone is used as the absorbent, generating gypsum as a by-product. Typically, FGD can achieve SO₂ removal efficiency more than 90%.

4.3. NO_x Emission and Changes Resulting from Different Scenarios

NO_x is the term used to describe the sum of nitric oxide (NO), nitrogen dioxide (NO₂), and other oxides of nitrogen. NO_x plays a major role in the formation of acid rain, secondary PM, ground level ozone, and smog in the atmosphere through a complex series of reactions with volatile organic compounds (VOCs), sunlight and water vapors. The Relationship between VOC and NO_x and O₃ has extensive studies [23-26]. NO_x also contributes to visibility impairment. The major sources of human-produced NO_x emissions are high-temperature combustion processes such as those that occur in electrical power plants and automobiles. Anthropogenic NO_x emissions in the US are estimated to total 22.2 Tg (as NO₂) per year,

with 53% from transportation, coal-fired plants are another major sources of NO_x because of the fuel they burn [27].

Figure 6 and **Figure 7** show the average NO_x emission flux and concentration in North-Eastern North America in summer season of 2001. The average NO_x emission flux was 0.20 mol/s in whole domain in the summer. Big cities such as Chicago, Detroit, and Toronto etc. have much more emission of NO_x than other areas, which arising from local motor vehicle emissions primarily. The biggest average NO_x concentration is 0.056 ppmv in Toronto city.

Figure 8 shows the average NO_x concentration simulating from three scenarios in the summer of 2001. The average NO_x concentration of base case in domain 2 is 0.00199 ppm in this summer. Average NO_x concentration getting from Scenario 2 in Toronto city change to 0.029 ppmv, this mean the emissions of coal-fired power plants from US can transport long distance through the

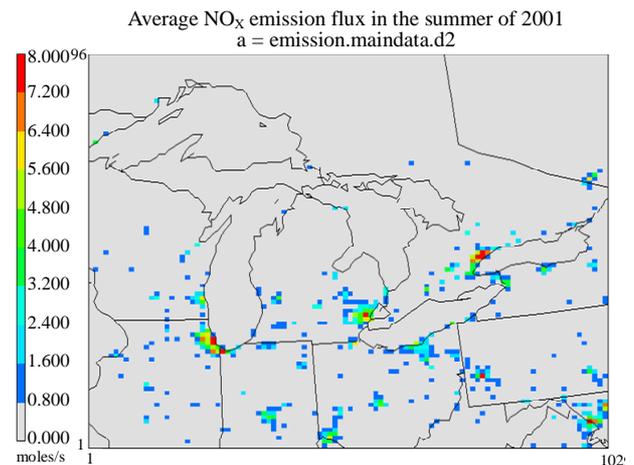


Figure 6. Average NO_x emission flux in summer season of 2001 in North-Eastern North America.

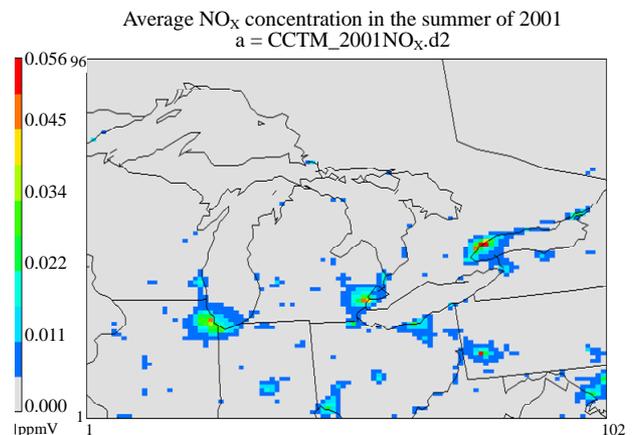


Figure 7. Average NO_x concentration in summer season of 2001 in North-Eastern North America.

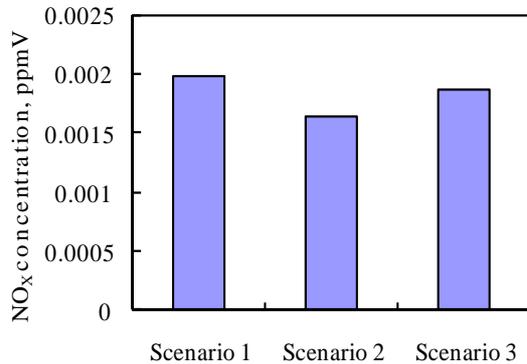


Figure 8. Average NO_x concentration simulating from different scenarios in the summer of 2001.

atmosphere to have obvious effect on Toronto. Average NO_x concentration getting from Scenario 2 and Scenario 3 is 0.00164 ppmv and 0.00187 ppmv. So, we can get coal-fired power plants from US and Canada contributing 17.6% and 6.0% for NO_x concentration in researched domain. This is lower with same EPA research results [20], coal-fired power plants contributed about 22% of all U.S. NO_x emissions in 2002, and this may be the cause of under-prediction of model for NO_x and the different object domain.

4.4. NO_x Emission Control from Coal-Fired Power Plants

In the past few years, EPA has promulgated several rules to reduce NO_x emissions, new rules for stationary sources (the Clean Air Interstate Rule, the Clean Air Mercury Rule, and the Clean Air Visibility Rule), as well as State plans to attain the National Ambient Air Quality Standard (NAAQS) of fine particle and ozone, will also significantly reduce future NO_x emissions. Beginning with the CAAA of 1990, existing generators also have faced increasingly stringent regulation of their nitrogen oxide (NO_x) emissions. Restrictions on summer emissions of NO_x from electricity generators in a majority of eastern states are expected to become even tighter during the next decade with the implementation of the call for amendments to state implementation plans (SIPs) from the US EPA, known as the NO_x SIP Call. This new regulation is designed to address the long-range transport of NO_x as a contributing factor to summer air pollution in cities on the East Coast. Recent lawsuits filed by EPA and New York State also have raised the possibility that many existing generating sources were negligent in not bringing their facilities into compliance with New Source Performance Standard (NSPS) when they made substantial investments enabling greater electricity generation at these facilities [28].

Reduction of NO_x emissions from industrial combus-

tion sources, especially coal-fired power plants is an important consideration in efforts undertaken to address the NO_x environmental concerns. New regulations announced by the US EPA facilitate utilities to develop new, efficient, and robust post-combustion NO_x control technologies [29]. The popular primary control technologies in use in the United States are low-NO_x burners (LNB) and over-fire air. The average NO_x reductions for specific primary controls have ranged from 35% to 63% from 1995 emissions levels. The secondary NO_x control technologies applied on U.S. coal-fired utility boilers include re-burning, selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) [30].

5. Conclusions

In this study, we use a regional atmospheric modeling system-CMAQ to compute the air quality effects of coal-fired power plants in North-Eastern North America. For the time period from May 1 to September 1, 2001, we consider three different scenarios to study the effects of SO₂ and NO_x emission from coal-fired power plants. The contributions of the coal plants for SO₂ and NO_x are found to be big, coal-fired power plants from US and Canada contribute 67.2% and 32.8% for SO₂ concentration, 17.6% and 6.0% for NO_x concentration in researched domain. The use of existing emission reduction rules and technologies can diminish the contributions of coal-fired power plants for total emission of SO₂ and NO_x. Further control measures for the emissions of SO₂ and NO_x from coal-fired power plants are necessary to reduce the negative environmental effects.

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7. References

- [1] L. Yang, I. Stulen, L. J. De Kok and Y. Zheng, "SO₂, NO_x and Acid Deposition Problems in China Impact on Agriculture," *Phyton-Annales Rei Botanicae*, Vol. 42, 2002, pp. 255-264.
- [2] M. V. Toro, L. V. Cremades and J. Calbo, "Relationship between VOC and NO_x Emissions and Chemical Production of Tropospheric Ozone in the Aburra Valley (Colombia)," *Chemosphere*. Vol. 65, No. 5, 2006, pp. 881-888.
- [3] F. B. Chaaban, T. Mezher and M. Ouwayjan, "Options for Emissions Reduction from Power Plants: An Economic Evaluation," *International Journal of Electrical Power & Energy Systems*, Vol. 26, No. 1, 2004, pp. 57-

- 63.
- [4] M. Victor, "Recent EPA Regulatory Actions and Effects on NO_x Controls," *Proceedings of the 2006 Environmental Controls Conference*, U.S. Department of Energy, National Energy Technology Laboratory, Pittsburgh, 2006, pp. 1-2.
- [5] J. R. Swinton, "Phase I Completed: An Empirical Assessment of the 1990 CAAA," *Environmental & Resource Economics*, Vol. 27, No. 3, 2004, pp. 227-246.
- [6] J. H. Goo, M. F. Irfan, S. D. Kim and S. C. Hong, "Effects of NO₂ and SO₂ on Selective Catalytic Reduction of Nitrogen Oxides by Ammonia," *Chemosphere*, Vol. 67, No. 4, 2007, pp. 718-723.
- [7] D. Stevenson and R. Dale, "Limestone FGD System Retrofit to San Juan Generating Station: Start-up Problems and Performance Following Start-up," *Combined Power Plant Air Pollutant Control Mega Symposium*, 2004, pp. 823-836.
- [8] J. M. Hao, L. T. Wang, M. J. Shen, L. Li and J. N. Hu, "Air Quality Impacts of Power Plant Emissions in Beijing," *Environmental Pollution*, Vol. 147, No. 2, 2007, pp. 401-408.
- [9] F. Mehdizadeh and H. S. Rifai, "Modeling Point Source Plumes at High Altitudes Using a Modified Gaussian Model," *Atmospheric Environment*, Vol. 38, No. 6, 2004, pp. 821-831.
- [10] R. P. Hermann, *et al.*, "Predicting Premature Mortality from New Power Plant Development in Virginia," *Archives of Environmental Health*, Vol. 59, No. 10, 2004, pp. 529-535.
- [11] M. J. Martin, *et al.*, "High Performance Air Pollution Modeling for a Power Plant Environment," *Parallel Computing*, Vol. 29, No. 11-12, 2003, pp. 1763-1790.
- [12] J. C. H. Fung, *et al.*, "Observational and Modeling Analysis of a Severe Air Pollution Episode in Western Hong Kong," *Journal of Geophysical Research*, Vol. 110, No. D9, 2005, p. 9105.
- [13] J. Chen, R. Bornstein and C. G. Lindsey, "Transport of a Power Plant Tracer Plume over Grand Canyon National Park," *Journal of Applied Meteorology*, Vol. 38, No. 8, 1999, pp. 1049-1068.
- [14] S. R. Springston, *et al.*, "Chemical Evolution of an Isolated Power Plant Plume during the TexAQS 2000 Study," *Atmospheric Environment*, Vol. 39, No. 19, 2005, pp. 3431-3443.
- [15] J. C. St John and W. L. Chameides, "Possible Role of Power Plant Plume Emissions in Fostering O₃ Exceedence Events in Atlanta, Georgia," *Journal of Geophysical Research*, Vol. 105, No. D7, 2000, pp. 9203-9211.
- [16] D. W. Byun and J. K. S. Ching, "Science Algorithms of the EPA Models-3 Community Multiscale Air Quality (CMAQ) Modeling System," U.S. Environmental Protection Agency, NERL, Research Triangle Park, 1999.
- [17] M. W. Gery, G. Z. Whitten, J. P. Killus and M. C. Dodge, "A Photochemical Kinetics Mechanism for Urban and Regional-Scale Computer Modeling," *Journal of Geophysical Research*, Vol. 94, No. D10, 1989, pp. 12925-12956.
- [18] M. Houyoux, J. Vukovich and J. Brandmeyer, "Sparse Matrix Kernel Emissions Modeling System: SMOKE User Manual," MCNC-North Carolina Supercomputing Center, 2000.
- [19] G. A. Grell, J. Dudhia and D. R. Stauffer, "A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5)," NCAR Technical Note, NCAR, Boulder, CO, 1995.
- [20] Y. R. Guo and S. Chen, "Terrain and Land Use for the Fifth-Generation Penn State/NCAR Mesoscale Modeling System (MM5): Program TERRAIN," NCAR/TN-397+IA NCAR Technical Note, National Center for Atmospheric Research, Boulder, 1994.
- [21] U.S.EPA, "Acid Rain Program 2002 Progress Report," EPA 430/R-03-011, Washington DC, 2003.
- [22] S. Napolitano, J. Schreifels, G. Stevens, M. Witt, M. LaCount, R. Forte and K. Smith, "The U.S. Acid Rain Program: Key Insights from the Design, Operation, and Assessment of a Cap-and-Trade Program," *The Electricity Journal*, Vol. 20, No. 7, 2007, pp. 47-58.
- [23] NAPAP, "NAPAP Report to Congress: An Integrated Assessment National Acid," Precipitation Assessment Program Office of the Director, Washington, D.C., 2005.
- [24] M. R. Taylor, E. S. Rubin and D. A. Hounshell, "Control of SO₂ Emissions from Power Plants: A Case of Induced Technological Innovation in the US," *Technological Forecasting and Social Change*, Vol. 72, No. 6, pp. 697-718, 2005.
- [25] Y. P. Peng, K. S. Chen, C. H. Lai, P. J. Lu and J. H. Kao, "Concentrations of H₂O₂ and HNO₃ and O₃-VOC-NO_x sensitivity in ambient air in southern Taiwan," *Atmospheric Environment*, Vol. 40, No. 35, 2006, pp. 6741-6751.
- [26] I. Filella and J. Penuelas, "Daily, Weekly and Seasonal Relationships among VOCs, NO_x and O₃ in a Semi-Urban Area near Barcelona," *Journal of Atmospheric Chemistry*, Vol. 54, No. 2, 2006, pp. 189-201.
- [27] A. F. Stein, E. Mantilla and M. M. Millan, "Using Measured and Modeled Indicators to Assess Ozone-NO_x-VOC Sensitivity in a Western Mediterranean Coastal Environment," *Atmospheric Environment*, Vol. 39, No. 37, 2005, pp. 7167-7180.
- [28] U.S. EPA, "National Air Quality and Emissions Trends Report, 1900-1998," EPA 454/R-00-003, U.S. Environmental Protection Agency, Washington, DC, 2000.
- [29] D. Burtraw, K. Palmer, R. Bharvirkar and A. Paul, "Restructuring and Cost of Reducing NO_x Emissions in Electricity Generation," Discussion Paper 01-10REV, Resources for the Future, Washington, DC, 2001.
- [30] Y. Fu and M. D. Urmila, "Cost Effective Environmental Control Technology for Utilities," *Advances in Environmental Research*, Vol. 8, No. 2, 2004, pp. 173-196.
- [31] R. K. Srivastava, R. E. Hall and S. Khan, "Nitrogen Oxides Emission Control Options for Coal-Fired Electric Utility Boilers," *Journal of the Air & Waste Management Association*, Vol. 55, No. 9, 2005, pp. 1367-1388.