

Estimating Air Quality Impacts of Elevated Point Source Emissions in Chongqing, China

Duoxing Yang^{1*,2} Zhongqiong Wang³, Renjian Zhang⁴

¹ *Institute of Crust Dynamics, CEA, Beijing, 100085, China*

² *Institute of Geology and Geophysics, CAS, Beijing, 100029, China*

³ *State Intellectual Property Office, Beijing, 100029, China*

⁴ *Institute of Atmosphere Physics, CAS, Beijing, 100029, China*

Abstract

In this study, the CALPUFF/MM5 modeling system was applied to estimate the air quality impacts of elevated point sources in 2004 in Chongqing. An intercomparison of the performance of CALPUFF against the observed data is discussed and an examination of scatter plots and QQ plots is provided. Results show that in 2004 the high emission contribution induced a relatively high contribution to average ambient concentration and significant impact on the urban area (higher than $10 \mu\text{g}/\text{m}^3$ of 24-hour averaged SO_2 concentration, maximum of $650 \mu\text{g}/\text{m}^3$). The highest 24-hour averaged SO_2 concentration exceeds the Grade NAAQS by 10.6%, 153.3%, 60% and 333.0% for January, April, July and October, respectively. The concentration distributions demonstrate the heterogeneity patterns in spatial and temporal scales due to significant topographic diversity and weather variations over short distances. The source of the SO_2 in the Chongqing area is local air pollution, which results from the lower effective stack height, low wind velocity in the area, basin topography, and the use of coal with high sulfur content. Parametric sensitivity analyses are still needed to determine the magnitude of uncertainty associated with CALPUFF.

Keywords: Point sources; Air quality; Chongqing; CALPUFF; Uncertainty.

INTRODUCTION

Air pollution in Chongqing has obviously been reduced since 2000, but it still has a long way to go and big challenges in air quality improvement (Guttikunda *et al.*, 2003).

*Corresponding author. Tel.: +86-10-62842631; Fax:

+86-10-62911045

E-mail address: yangduoxing@yahoo.com

A coal-dominated energy structure is one of the major causes of air pollution in Chongqing and elevated point sources take about two-thirds of the total coal consumption. Elevated point sources are significant emitters of sulfur dioxide (SO_2), which is harmful at high concentrations and contributes to the formation of atmospheric fine particulates. It is estimated that

Chongqing's elevated point sources emitted 75.6% of the total SO₂ emission (Chongqing EPA, 2004). Evaluating the air quality impact of these elevated point sources is a necessary step in the design of a comprehensive cost effective air pollution control strategy in Chongqing.

Although several studies have estimated the air quality impacts for elevated point sources (e.g., power plants) emissions in China (Zhou *et al.*, 2003, 2006; Hao *et al.*, 2007), they could well differ in Chongqing settings, because of differences in stack characteristics, topography and meteorology. There are several relevant pieces of research into this area (Lei *et al.*, 1987; Gao *et al.*, 2000). In the study of (Gao *et al.*, 2000), a Eulerian sulfur deposition model was used to study the distributions of sulfur pollutants in East Asia, and it was revealed that a big SO₂ value area lies in Sichuan basin with the biggest level of 47.3 µg/m³ near Chongqing. But the spatial resolution of this model was low and the SO₂ emission inventory applied wasn't full, especially for Chongqing. In addition, this study couldn't take into account single contribution from elevated point sources to local SO₂ levels in Chongqing. One study (Lei *et al.*, 1987) modeled SO₂ air pollution from all anthropogenic sources, but only the urban area, 12% of whole Chongqing area, was covered. On the other hand, this study applied its model with meteorological data from one station, which couldn't capture the relatively real meteorological variations over

short distances. Currently available air quality estimates from Chongqing used simplified models (e.g., Gaussian plume model), which may not capture the full impact of a pollution source. With the increment of older fossil-fuel elevated point sources, the impact of this large emission sector on Chongqing's air quality needs further assessment.

In this study we focus on the air quality impact of Chongqing local elevated point sources to the Chongqing area. Emissions of SO₂ in 2004 were estimated using monitored emission factors.

The CALPUFF/MM5 modeling system was applied to model the concentration increments of SO₂. The aim of this study has been to evaluate current status of the air pollution from elevated point sources in Chongqing, and gain information on the necessity for further control.

METHODS

Modeling structure

The CALPUFF/MM5 modeling system, which is commonly used in air quality impact studies dealing with routine industrial releases, was deployed to simulate the meteorology as well as pollutant dispersion and transport in Chongqing. There are several reasons for choosing this model. Firstly, it has the ability to generate and handle complex three-dimensional wind fields and has the complex terrain algorithm (Scire *et al.*, 1999a), which is necessary

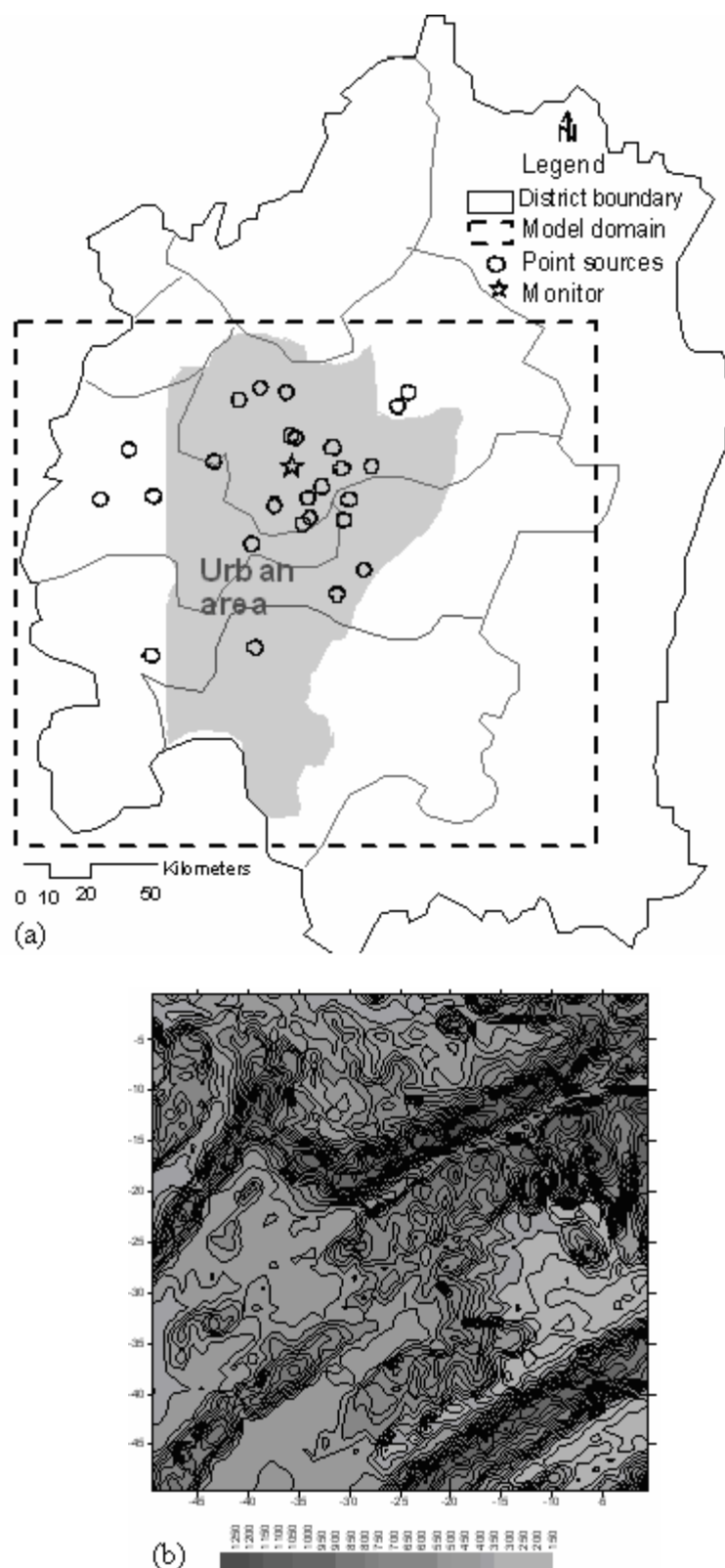


Fig. 1. (a) Domain coverage and locations of elevated point sources; (b) terrain characteristics (m) in Chongqing. Area in gray color is the urban area of Chongqing. Also shown is the location of the monitor site (open star).

when the modeling domain is expanded to whole Chongqing area. Secondly, it can treat calm wind conditions (< 1.0 m/s), the frequency of which in Chongqing is about 47% (Tao *et al.*, 2006). This allows the modeling of both primary and secondary pollutants and is not too complex to apply to evaluate a single sector, as CAMx or CMAQ, is also attractive.

CALMET is a diagnostic wind field model that produces hourly ranges of meteorological parameters, including wind, temperature, mixing height and dispersion properties on a three-dimensional gridded modeling domain by interpolating routine surface and upper-air meteorological data. The data interpolation accounts for the blocking effects of terrain and slope flows. It also ensures the preservation of air-mass continuity (Scire *et al.*, 1999a). Since diagnostic models interpolate observational data, they are critically dependent on the quality and density of the observations. The CALMET model can ingest prognostic model outputs, such as the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5), and has displayed improved predictions of certain variables (Chandrasekar *et al.*, 2003). Hence, to develop meteorological data for CALMET, the MM5 version 3.7 was used.

The CALPUFF model is an advanced Lagrangian-Gaussian non-steady state air-quality model, promulgated by the U.S. Environmental Protection Agency (U.S. EPA) as the regulatory model for assessing the long-range transport of pollutants and their impacts, on a case-by-case basis, for

certain near and far-field applications involving complex meteorological conditions (Scire *et al.*, 2000). It simulates continuous puffs of pollutants released from a source into the ambient wind flow. As the wind flow changes from hour to hour and from place to place, the path of the puff changes according to the new wind flow direction. Puff diffusion is Gaussian, and concentrations are based on the contribution of each puff as it passes over or near a receptor point (Scire *et al.*, 1999b).

Domain coverage

For this study, we evaluated the aggregate impacts of elevated point sources in Chongqing. The southwest corner of the domain is located at longitude 107.7E, latitude 31.4N; the northeast corner is located at longitude 108.3E, latitude 32.0N. There are 1000 receptor points in both the X and Y directions, with a grid spacing of 0.05 km (Fig. 1). The entire domain, 50 km \times 50 km, covers most of Chongqing's area and all its heavily populated regions with Lambert projection.

Source characteristics and emissions

In this study we evaluate the aggregated air quality impacts of all the elevated point sources in Chongqing in 2004. There are 29 elevated point sources (including three public power plants, the total generating capacity is 2920 MW) at present. The power plants provided about 48% of the total electricity consumption in Chongqing in 2004. All point sources are coal burning

Table 1. Stack and emissions characteristics of elevated point sources in Chongqing.

| Plant | Fuel | Stack height (m) | Stack inner diameter (m) | Exist temperature (K) | Volume flux (m ³ /h) | SO ₂ emission (ton/year) |
|-------|-----------|------------------|--------------------------|-----------------------|---------------------------------|-------------------------------------|
| 1 | Coal fuel | 240 | 3.0 | 422 | 897900.00 | 40098.72 |
| 2 | Coal fuel | 240 | 6.0 | 422 | 1607041.00 | 24988.00 |
| 3 | Coal fuel | 150 | 1.8 | 414 | 630008.12 | 1802.69 |
| 4 | Coal fuel | 120 | 1.8 | 445 | 241660.60 | 1453.28 |
| 5 | Coal fuel | 110 | 1.8 | 450 | 14042.24 | 86.19 |
| 6 | Coal fuel | 105 | 1.8 | 338 | 28084.47 | 172.38 |
| 7 | Coal fuel | 100 | 0.9 | 387 | 41580.00 | 751.79 |
| 8 | Coal fuel | 100 | 1.8 | 337 | 59446.89 | 455.40 |
| 9 | Coal fuel | 100 | 1.4 | 337 | 76087.53 | 185.78 |
| 10 | Coal fuel | 95 | 1.8 | 331 | 157118.60 | 964.37 |
| 11 | Coal fuel | 80 | 1.3 | 377 | 208383.54 | 1029.63 |
| 12 | Coal fuel | 80 | 1.8 | 377 | 59779.68 | 158.63 |
| 13 | Coal fuel | 80 | 1.5 | 377 | 23675.00 | 79.56 |
| 14 | Coal fuel | 67 | 1.2 | 377 | 45115.00 | 85.21 |
| 15 | Coal fuel | 60 | 1.2 | 331 | 18301.57 | 516.67 |
| 16 | Coal fuel | 60 | 1.0 | 331 | 80881.48 | 262.63 |
| 17 | Coal fuel | 60 | 1.2 | 331 | 55840.00 | 253.40 |
| 18 | Coal fuel | 60 | 1.2 | 328 | 57298.52 | 65.34 |
| 19 | Coal fuel | 60 | 1.0 | 328 | 1491.17 | 0.74 |
| 20 | Coal fuel | 50 | 1.2 | 387 | 11400.00 | 230.40 |
| 21 | Coal fuel | 50 | 3.1 | 387 | 3978.00 | 100.48 |
| 22 | Coal fuel | 50 | 0.8 | 387 | 8041.10 | 52.98 |
| 23 | Coal fuel | 45 | 1.2 | 331 | 5522.65 | 58.29 |
| 24 | Coal fuel | 45 | 1.2 | 331 | 1818.00 | 39.85 |
| 25 | Coal fuel | 45 | 1.2 | 331 | 1209.60 | 33.12 |
| 26 | Coal fuel | 45 | 1.0 | 317 | 12376.71 | 30.46 |
| 27 | Coal fuel | 45 | 2.2 | 317 | 2542.75 | 10.22 |
| 28 | Coal fuel | 45 | 1.4 | 373 | 3880.01 | 9.19 |
| 29 | Coal fuel | 45 | 2.0 | 373 | 502.00 | 3.41 |
| Total | | | | | | 73978.81 |

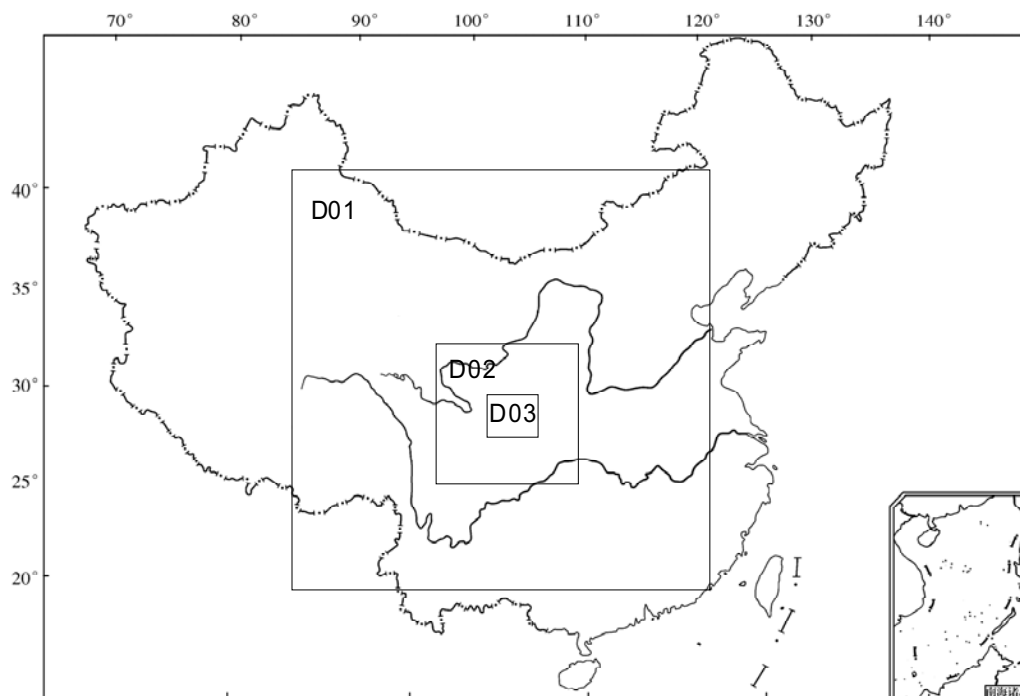


Fig. 2. MM5 Nested Computational Domain (D01: 27-km grid-cell resolution, D02: 9-km grid-cell resolution, D03: 3-km grid-cell resolution).

(older fossil-fueled). Fig. 1 shows the locations of these elevated point sources. Most of them are in urban area. It not only induces air pollution in the most populous area, but also influences the cityscape of the political, cultural and commercial center of Chongqing. Source characteristics and emissions of these elevated point sources are summarized in Table 1. In 2004, these 29 stacks emitted 75.56% of the total SO₂ emissions, which reached to 97902.95 ton. Of the total emissions 22.47% resulted from local area sources, accounting for 22000 tons. Contribution to total SO₂ emissions from other uncounted 22 stacks (1824.14 tons) was about 1.86%. Therefore, these 29 stacks were the dominant contributor of SO₂

in 2004. According to Chongqing EPA (2004), the emission rates of these 29 stacks remain constant for each month of the year.

METEOROLOGY MODEL CONFIGURATION

MM5

Fig. 2 depicts the modeling domain for MM5. The model domain has 32 vertical levels, going up to about 13 km AGL, with vertical grid spacing stretched from about 20 m near the ground to 800 m near the top of the domain. This allowed CALMET to interpolate from a higher- to a lower-resolution grid (since CALMET uses ten vertical layers). One-way nesting was used

to generate ambient wind fields at multiple grid-cell resolutions (27-, 9-, 3-km) as shown in Fig. 2. For each domain, the basic coordinate grid for MM5 consisted of 103 grid cells along the x-axis (east-west) and 103 grid cells along the y-axis (north-south), with the center point of the model domain set to (31.378°N, 108.238°E).

The meteorological data input for initialization included the NCEP global surface observations data, as well as the NCEP global upper air observation data. The medium-range forecast (MRF) boundary-layer scheme and a cloud-radiation scheme that accounts for long- and short-wave radiative transfers were employed. Deep convection was represented on 27-km and 9-km resolution domains using the Kain-Fritsch scheme. All three domains used an explicit microphysical scheme, with a simple ice phase to represent resolved-scale saturated processes. The NCEP Final Analysis (FNL) data archived at NCAR is for every six hours at a spatial resolution of $1^\circ \times 1^\circ$ at standard pressure levels under 100 hPa. The data include two-dimensional variables, including sea surface temperature and sea level pressure, and three-dimensional variables of temperature, geopotential height, U and V components, and relative humidity.

CALMET

The CALMET domain was the same as the final CALPUFF domain as described in Section 2.3 and the Lambert Conformal map projection was used to account for the

earth's curvature. The two standard parallel latitudes were set at 20N and 60N. The reference longitude and latitude were set at 100E and 25N. These quantities were used to adjust observed and prognostic winds to fit the Lambert Conformal mapping. CALMET uses fewer vertical layers than MM5, in part because air pollution modeling does not require detailed information on the upper atmosphere. Ten vertical layers with cell face heights at 0, 20, 40, 80, 160, 320, 640, 1000, 1500, 2200 and 3000 m were used in the CALMET runs. Due to lack of available meteorological observation data, the MM5 was used in this study to develop high-resolution, three-dimensional meteorological fields (i.e., wind, temperature, pressure, etc.). MM5-generated meteorological fields are used to drive the CALMET model which can use important information contained in MM5 data to resolve terrain features, such as terrain channeling and gravity-driven slope flows (Yang et al., 2006). CALMET automatically interpolated from the MM5 model grid system to the CALMET grid. In our case, the gridded geophysical data, including terrain height and land-use category, were generated from USGS terrain and land-use database (www.usgs.gov).

CALPUFF

CALPUFF is a Lagrangian, non-steady-state, gridded puff model for modeling the transport, dispersion, chemical reactions and deposition of air pollutants in the atmosphere. In this study, SO₂ was modeled.

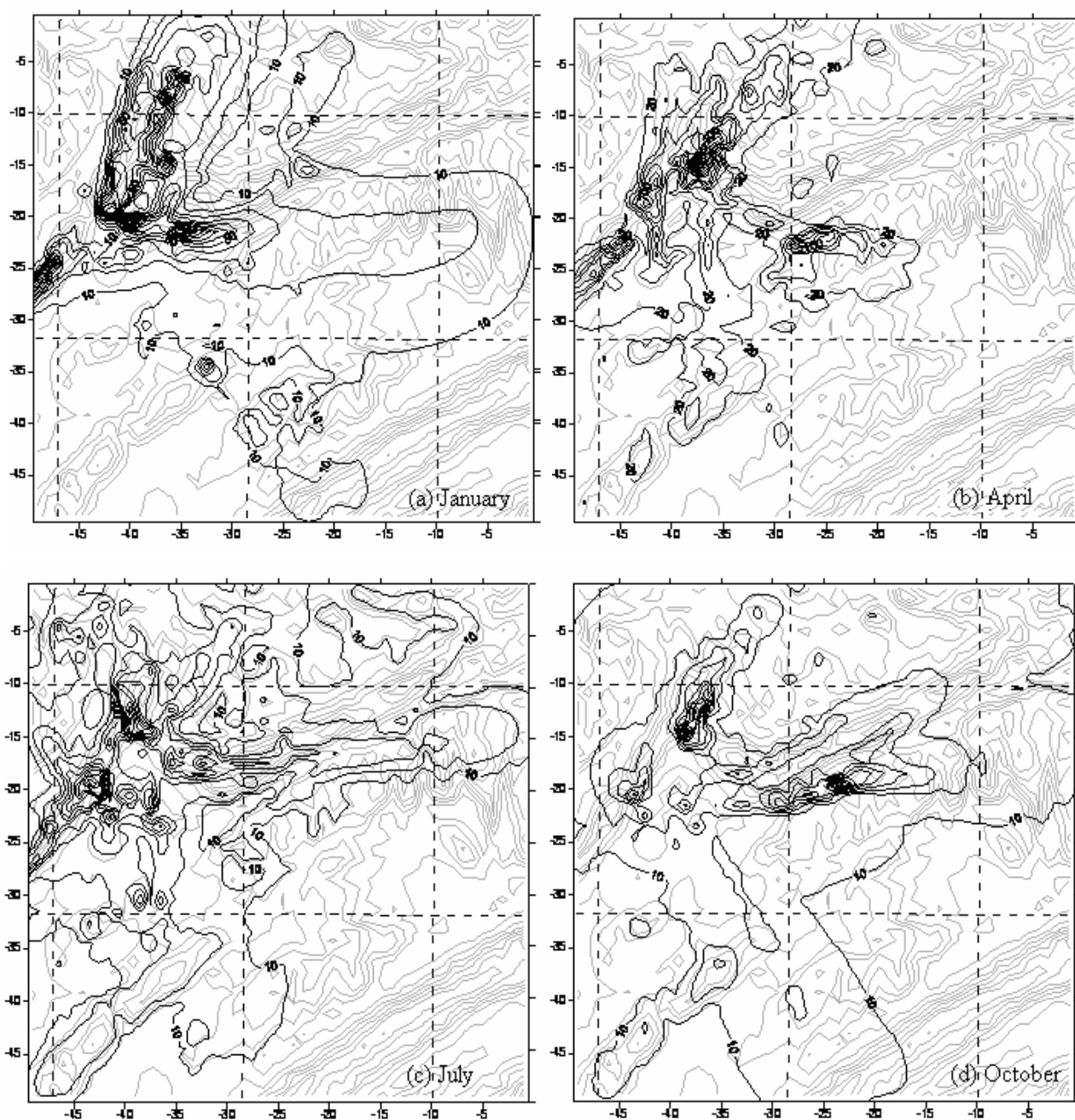


Fig. 3. (a-d) Maximum 24-hour averaged SO_2 concentration increments ($\mu\text{g}/\text{m}^3$) by elevated point source emissions in Chongqing in 2004. Gray background represents the terrain elevation.

MESOPUFF II chemical mechanism was chosen and hourly ozone monitoring data were input into the model to estimate the daytime oxidation of SO_2 . Under this chemical transformation method, daytime SO_2 oxidation is an hourly varying function

of background ozone concentration, solar radiation, atmospheric stability, and relative humidity, with a night-time rate of 0.2 percent/h (Zhou *et al.*, 2003). The plume rise, stack tip downwash and vertical wind shear above the stack top were taken into account

in our study. Dry deposition of SO₂ was calculated by using the model default values, such as diffusivity, reactivity, resistance and solubility. For wet deposition, CALPUFF uses an empirically based scavenging coefficient method. We used CALPUFF default scavenging coefficients for SO₂, with liquid precipitation coefficients of 3×10^{-5} (Zhou et al., 2003; Hao et al., 2007).

Length of simulation

The year 2004 was chosen for the analyses. We calculated SO₂ concentration for one period in each of the four seasons, which were 1-31 January, 1-30 April, 1-31 July, and 1-31 October, respectively.

RESULTS AND DISCUSSION

Model validation

The modeling system was evaluated comprehensively to ensure reasonable estimates of ambient SO₂. We present a time series of the SO₂ concentrations at the monitor denoted by the star as shown in Fig. 5. For example, Fig. 5a compares hourly values (mg/m³) (from January 1-31, 2004) for the monitor against the modeled estimates for the grid cell in which that monitor is located. At first glance, the SO₂ prediction seemed to be in relatively good agreement with the observed data. Fig. 5b shows the scatter plots of the modeled concentrations versus the observed values. The straight line in Fig. 5a is computed by linear regression of the modeled concentrations according to the relation:

$$C_{cal} = 0.43C_{obs} \pm 0.06 \quad (1)$$

where C_{cal} and C_{obs} are the modeled and observed concentrations, respectively, in mg/m³. Fig. 5c shows the quantile-quantile (QQ) plots of the predicted versus observed concentrations. It shows that the model performed well in predicting SO₂. Note that the monitor and model are in fact providing SO₂ levels at different locations, as the monitor reflects concentrations at a single point location and the modeled estimate reflects the average over a 0.05 km by 0.05 km grid cell. From Figs. 5a-5c we also see that the model tends to underestimate SO₂. This was primarily due to the fact that we just accounted for the SO₂ emissions contributed by 29 elevated point sources in the emission inventory. Besides uncertainties in meteorology and emissions, some plausible cause for the difference is that dry and wet depositions, as well as chemical formation, of SO₂ might not be sufficiently represented in the model. Uncertainties could arise through influence of the model grid resolution on the calculated results.

SO₂ concentrations

Fig. 3 (a-d) depicts the patterns and magnitudes of the maximum 24-hour averaged sulfur dioxide concentration increments for each season. As anticipated, the concentration increments for sulfur dioxide are heterogeneous with concentrations peaking further from the source and diminishing more slowly with distance from the source. It's seen from Fig.

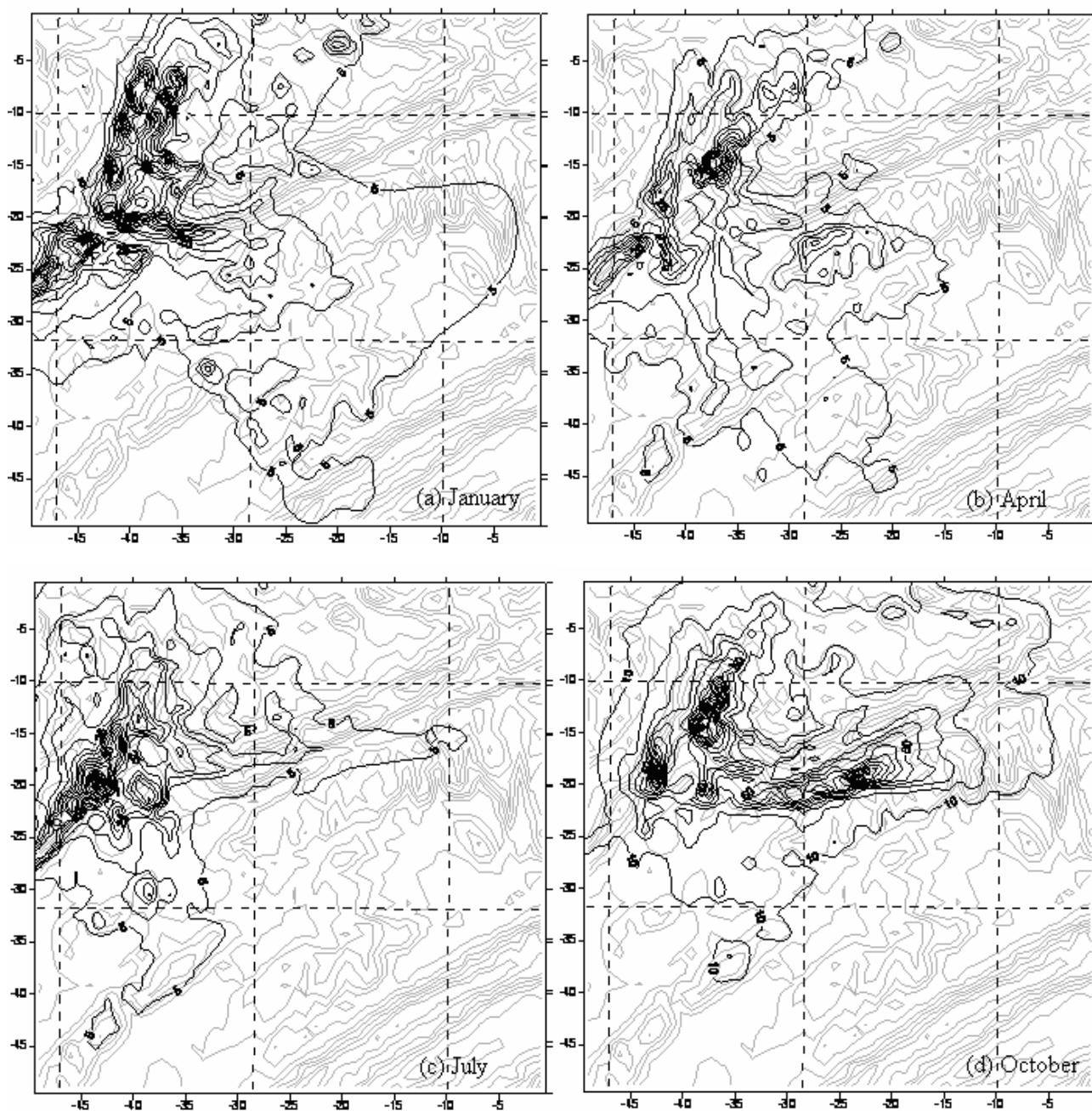


Fig. 4. (a-d) Monthly averaged SO₂ concentration increments ($\mu\text{g}/\text{m}^3$) by elevated point source emissions in Chongqing in 2004. Gray background represents the terrain elevation.

3 that the CALPUFF simulation predicts concentrations mostly in the northwest region of Chongqing in amounts between 10 and $160 \mu\text{g}/\text{m}^3$ during February. From April 1 to 30, sulfur dioxide concentration mainly distributed in the west, with values ranging

from 20 to $380 \mu\text{g}/\text{m}^3$. The highest SO₂ concentration is $380 \mu\text{g}/\text{m}^3$, which already exceeds the Grade NAAQS (National Atmospheric Ambient Quality Standard) ($150 \mu\text{g}/\text{m}^3$). The high concentration area shrinks greatly. As for July, the sulfur

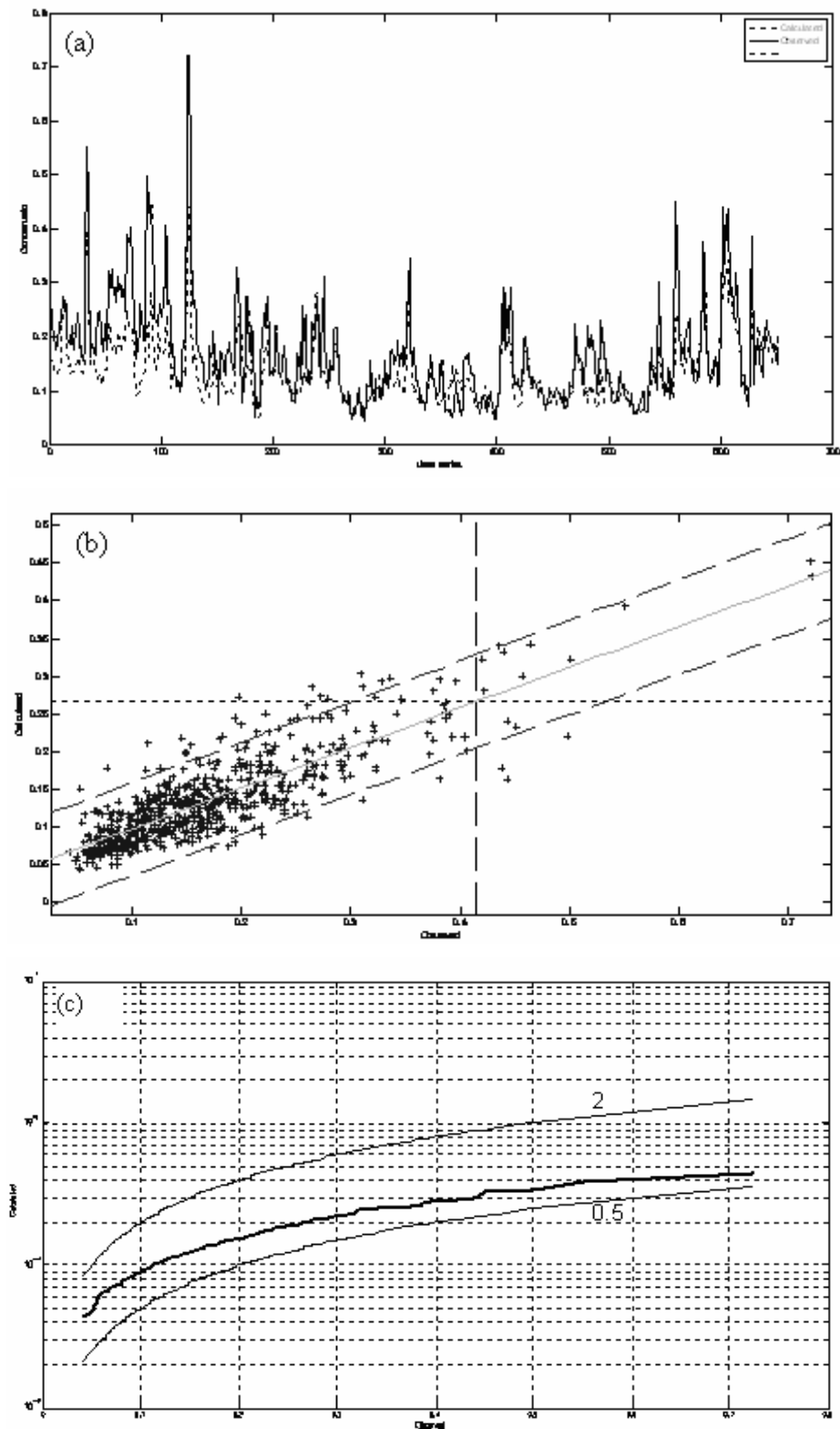


Fig. 5. (a) Time series of CALPUFF predicted (dot line) and observed SO₂ concentrations (solid line) at the monitor from 1 to 31, January, 2004 (mg/m³); (b) Scatter plots of modeled versus observed concentrations (mg/m³); (c) Quantile-quantile plots of modeled versus observed concentrations (mg/m³).

dioxide concentration varied from 10 to 240 $\mu\text{g}/\text{m}^3$ and the influenced area gradually expanded. The highest SO_2 concentration reached 240 $\mu\text{g}/\text{m}^3$, equaling the 160% SO_2 standard. During October the SO_2 concentration ranged between 10 and 650 $\mu\text{g}/\text{m}^3$. The highest SO_2 concentration was 650 $\mu\text{g}/\text{m}^3$, equaling to 433% of the SO_2 standard. The influenced area almost covered the whole study region. Given the complex terrain and wind field variation affecting air pollution distribution, the concentration distributions show heterogeneity patterns in spatial and temporal scales. The sulfur dioxide concentration was higher in the valley than on the mountain, because of meteorological parameters impacting both the deposition processes and the transport phenomena, which govern the evolution of these distributions. Another cause is that SO_2 is heavier than air, it tends to accumulate in low-lying areas.

Fig. 4 (a-d) shows the characteristics of monthly averaged sulfur dioxide concentration. During February the concentration dominated in the southeast and northwest regions, and the values changed from 5 to 65 $\mu\text{g}/\text{m}^3$. In April, the distribution tendency was the same as that of February, but the influenced area decreased. During July, the concentration increased from 5 to 105 $\mu\text{g}/\text{m}^3$, and the influenced area shifted to the western region. The concentration in October became distributed in the north of Chongqing, with values varying from 10 to 180 $\mu\text{g}/\text{m}^3$. This

demonstrated that the atmospheric dispersion conditions were better in April than other seasons. The 24-hour and monthly averages of SO_2 presented in Figs. 3 and 4 were calculated according to the formulation provided by the state environmental agency of China (SEPA) (1993).

Discussion

As shown in Figs. 3 and 4, the averaged SO_2 concentrations vary even in a range of two orders in magnitude. The higher concentration appears near the power plants and the most polluted areas are northwest of urban area. The central urban area is the second most polluted region. Many factors may contribute to this difference, such as meteorological conditions, proximity of heavily polluted point sources to receptors, and the geographic domains deployed in each study. The three power plants have a significant influence on SO_2 concentration in the west and central urban area due to their intensive urban locations. Of the total SO_2 emitted from 29 stacks 92.38% resulted from the three power plants. Pollution from the power plants cannot be neglected for this area if it is to reach the air quality standard. As seen from Figs. 3 and 4, the less polluted areas are southeast of the urban area due to the fact that this area is far away from the three power plants, and the local meteorological conditions don't support the long distance transport of the SO_2 emissions. Unfortunately, given the lack of available observed data, a comparison between these

discrepancies can't be performed. Efforts to improve the observed data should be undertaken in future studies of this sort.

It is inferred from the calculated results that sulfur dioxide concentration distribution is characterized by significant topographic diversity and climate variations over short distances. Strongly stratified local meteorological circulation can result in very complex surface and boundary layer meteorology (Yang *et al.*, 2007). Calm conditions, surface-based upper air inversions and mesoscale, thermally driven wind flow, such as mountain-valley breezes are reasonably frequent. Mountain-valley features, especially during cold, stable winter days can result in significant potential for elevated air pollution levels (Yang *et al.*, 2006).

Difficulties associated with the lack of information on certain modeling input parameters should be reiterated, given that it was the largest estimated source of uncertainty associated with modeling. For example, there are some of the primary elements of parametric uncertainty within our CALPUFF application. This includes uncertainties that can be quantified (e.g., the incorporation of wet and dry deposition, the choice of chemical conversion mechanism, background pollution concentrations, and the size of the receptor region) and uncertainties in the meteorological data (Levy *et al.*, 2002). For deposition, we would expect substantial uncertainty in the plume depletion terms that produce wet and dry deposition losses. Past researchers have

found that uncertainties of at least an order of magnitude exist for dry deposition of small particles (Levy *et al.*, 2002) and that dry deposition velocity and scavenging coefficients range by two to three orders of magnitude across studies (McMahon *et al.*, 1979). Wet deposition would be expected to be just as uncertain, especially related to the uncertainties involved with setting scavenging coefficients. Thus, even ignoring the fact that a deposition-based impact model should include indirect exposure pathways and environmental degradation associated with acid precipitation, our baseline model using CALPUFF-default deposition parameters could underestimate total impacts if deposition is overstated.

As for the size of the receptor region, which consisted of points within approximately 50 km (a range not evaluated in tracer dispersion experiments) of the point sources. It is unclear whether this choice might result in an overestimate of impacts. On the first point, tracer dispersion experiments have shown that CALPUFF is reasonably unbiased between 50 and 200 km but may tend to overestimate concentrations for greater transport distances by as much as a factor of 2, given the lack of accounting for nocturnal wind shear effects on enhanced dispersion (US EPA., 1999b). Uncertainties resulting from 22 uncounted stacks could underestimate total SO₂ impacts by 1.86%.

As to mitigating SO₂, control measures such as fuel substitution and flue gas desulfurization will greatly mitigate the SO₂, especially alleviating the pressure on the

urban area to reach the National Atmospheric Ambient Quality Standard (NAAQS). Desulfurization measures taken before 2010 will reduce SO₂ emission by 94%, which will greatly mitigate the SO₂ pollution. Therefore, the highest 24-hour averaged SO₂ concentration decreases to 39 µg/m³. SO₂ pollution will be mitigated with 333% decrease in concentration for reaching the 24-hour averaged SO₂ concentration standard. It should be worthwhile assessing the individual contributions of the 29 point sources to the surface SO₂ concentrations. The sensitivity of source reduction to the improvement of SO₂ concentrations should be demonstrated in detail in future studies of this sort.

Nevertheless, this is the first time the elevated point source induced plumes were simulated using CALPUFF in Chongqing. The study points to some critical auxiliary information needed for satisfactory modeling of sulfur dioxide concentration, which needed to be estimated in the present study due to lack of availability. Future studies can be directed to fill in such knowledge gaps.

CONCLUSIONS

The CALPUFF dispersion model was applied to estimate the air quality impacts associated with current SO₂ emissions from a set of 29 elevated point sources in the Chongqing area in 2004. Results show that these point sources provide maximum 24-hour averaged SO₂ concentration increments

of up to 10 µg/m³ (maximum increment of 650 µg/m³), with monthly averaged values of up to 5 µg/m³ (maximum increment of 180 µg/m³). In 2004, the emission contribution of the point sources had a large impact on Chongqing's average ambient concentration. In some local areas, especially the west and most populous middle urban, they produced notable SO₂ pollution. Concentration distributions show heterogeneity patterns in spatial and temporal scales due to significant topographic diversity and climate variations over short distances. The magnitude of these concentration increments is potentially significant and illustrates that accurate long-range dispersion modeling can provide meaningful and policy-relevant information for the regulatory community. It points out that further investigation is needed to determine the magnitude of uncertainty associated with CALPUFF (e.g., deposition parameters, chemical conversion mechanism) by using parametric sensitivity analyses.

ACKNOWLEDGMENTS

This project research was sponsored by Institute of Crustal Dynamics, CEA (project number: ZDJ2008-08) and CSTC (Project NO. 2005AC7097). The authors greatly appreciate Dr. Chuen-Jinn Tsai, as well as the anonymous reviewers for their comments which have much improved this manuscript. We also thank Dr. Gangcai Chen for providing the emission inventory and the observed data.

GLOSSARY

CALPUFF: An advanced non-steady-state meteorological and air quality modeling system developed by ASG scientists. The main components of the modeling system are CALMET (a diagnostic 3-dimensional meteorological model), CALPUFF (an air quality dispersion model), and CALPOST (a post-processing package).

CALMET: One of the main components of the CALPUFF modeling system, a diagnostic 3-dimensional meteorological model.

MM5: Fifth-generation PSU/NCAR mesoscale model.

FNL: Final Analysis.

NCEP: National Centers for Environmental Prediction.

NCAR: National Center for Atmospheric Research.

AGL: Above ground level.

CMAQ: Community Model of Air Quality.

EPA: Environmental Protection Agency.

CAMx: Comprehensive Air Quality Model with Extensions.

NAAQS: National Atmospheric Ambient Quality Standard.

MESOPUFF: Mesoscale Puff Model.

MRF: Medium-range forecast.

REFERENCES

Chongqing Municipality Environment Protection Bureau (Chongqing EPA),

(2004). *Chongqing Environmental Quality Bulletin in 2004*. 9-12.

Chandrasekar, A., Philbrick, C.R., Clark, R., Doddridge, B. and Georgopoulos, P. (2003). Evaluating the Performance of a Computationally Efficient MM5/CALMET System for Developing Wind Field Inputs to Air Quality Models. *Atmos. Environ.* 37: 3267-3276

Gao, H.W., Huang, M.Y. and An, J.L. (2000). Distribution of Sulfur Pollutants in East Asia. *Chin. Geogr. Sci.* 10: 38-43.

Guttikunda, S.K., Carmichael, G.R., Calori, G., Eck, C. and Woo, J.H. (2003). The Contribution of Megacities to Regional Sulfur Pollution in Asia. *Atmos. Environ.* 37: 11-12.

Lei, X.E., Jia, X.Y., Yuan, S.Z., Luo, Q.R., Chen, S.L. and Xu, Y. (1987). A Numerical Simulation of the Distribution of Acid Precipitation in Chongqing Area of China. *J. Atmos. Sci.* 4: 313-322.

Levy, J.I., Spengler, J.D., Hlinka, D., Sullivan, D. and Moon, D. (2002). Using CALPUFF to Evaluate the Impacts of Power Plant Emissions in Illinois: Model Sensitivity and Implications. *Atmos. Environ.* 36: 1063-1075.

McMahon, T.A. and Denison, P.J. (1979). Review Paper: Empirical Atmospheric Deposition Parameters: A Survey. *Atmos. Environ.* 13: 571-585.

Hao, J.M., Wang, L.M., Shen, M.J., Li, L. and Hu, J.H. (2007). Air Quality Impacts of Power Plant Emissions in Beijing. *Environ. Pollut.* 147: 401-408.

- Scire, J.S., Strimaitis, D.G. and Yamartino, R.J. (2000). *A User's Guide for the CALPUFF Dispersion Model (Version 5)*. Earth Tech Inc.
- Scire, J.S., Robe, F.R., Fernau, F.R. and Yamartino, R.J. (1999a). *A User's Guide for the CALMET Meteorological Model (version 5.0)*. Earth Tech Inc.
- Scire, J.S., Strimaitis, D.G. and Yamartino, R.J. (1999b). *A User's Guide for the CALPUFF Dispersion Model (version 5.0)*. Earth Tech Inc.
- SEPA, (1993): Technical Guidelines for Environmental Impact Assessment of P.R. China-Air Environment, HJ/T 2.2-9. State Environmental Protection Administration (SEPA), Publication of *China Environ. Sci.* Beijing.
- Tao, J., Chen, G.C. and Zhong, C.Q. (2006). Sources Apportionment of TSP in Chongqing. *Journal of the Graduate School of the Chinese Academy of Sciences*. 23: 489-493.
- US Environmental Protection Agency, (1999b). Interagency Workgroup on Air Quality Modeling (IWAQM) Phase 2 Summary Report and Recommendations for Modeling Long Range Transport Impacts. EPA-454-R-98-019, <http://www.epa.gov/scram001> (under 7th Modeling Conference).
- Yang, D.X., Chen, G.C. and Zhang, R.J. (2006). Estimated Public Health Exposure to H₂S Emissions from a Sour Gas Well Blowout in Kaixian County, China. *Aerosol and Air Qual. Res.* 6(4): 430-443.
- Yang, D.X., Han, Y.W., Gao, J.X. and Jesse, T. (2007). Transport of Airborne Particulate Matters Originating from Mentougou, Beijing, China. *China Particuology*. 5: 408-413.
- Zhou, Y., Levy, J.I., Hammitt, J.K. and Evans, J.S. (2003). Estimating Population Exposure to Power Plant Emissions Using CALPUFF: A Case Study in Beijing, China. *Atmos. Environ.* 37: 815-826.
- Zhou, Y., Levy, J.I., Evans, J.S. and Hammitt, J.K. (2006). The Influence of Geographic Location on Population Exposure to Emissions from Power Plants throughout China. *Environ. Int.* 32: 365-373.

Received for review, February 19, 2008

Accepted, July 8, 2008