Impacts of different emission sources on air quality during March 2001 in the Pearl River Delta (PRD) region

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Abstract

This study focuses on the role played by emissions from transportation, industry and power generation on the concentrations of O3, CO, NO, NOx and SO2 in Guangdong province of China. Observational data of the pollutants and numerical modeling of atmospheric chemistry, transport and removal processes with STEM-2K1 and MM5 are used for March 2001. The objective is to identify the relative importance of the three emission sources on the concentrations of the pollutants. In addition, the relative importance of NOx and VOC emissions from the transportation sector for O3 production is examined. The observations at a rural and an urban site in the region show distinctive characteristics, indicating the importance of local emissions. A comparison of the observed ratios of CO/NOx and SO2/NOx at the two sites with those derived from the emission inventories show the usefulness of the emission inventories. A control simulation with all emissions included shows a fairly satisfactory performance of the model in terms of the comparison between the observed and modeled concentrations of CO, SO2, NOx and O3 at the rural site, although the observed extremes are less well simulated. Three simulations with different emission scenarios suggest that the transportation source was the main contributor to NOx, CO and O3 concentrations accounting for 34.2%, 33.1% and 17.8% of their total concentrations, respectively. For SO2 concentration, the main contributor is the power plant sources with a contribution rate of 32.9%. For SO2, the doubling of emissions from the industry has a much larger effect on the ambient levels than the doubling from the transportation, whereas the increase in the transportation sector sources has approximately twice the effect of the increased industrial emission on O3. The doubling of emissions from the transportation and industry sources would increase the O3 concentration by about 26.7% and 8.5% for the whole region. Finally, the O3/NOx ratio of 25 was found to be a reasonable threshold to separate NOx-limited and VOC-limited regimes concerning O3 chemistry. It is found that the urban area is VOC-limited and the non-urban area is NOx-limited. These results have implications for O3 control strategy for the region.

Keywords: Air quality; Photochemical smog; Emission sources; Pearl River Delta; China

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1. Introduction

Air pollution generated by human activities presents one of the most serious problems in many parts of the world, including large parts of China. It has adversely affected the lives of millions of people and caused great economic damage to ecosystems and society (e.g. T. Wang et al., 2003a,b; X. Wang et al., 2003). China is under rapid development in recent decades (Wang et al., 2000). This is especially true for the coastal areas such as those in southern China. The rapid and recent industrialization of southern China has resulted in serious local environment problems (Wong et al., 2003). The large emissions of pollutants from China also have implications for neighboring countries (e.g. Murano et al., 2000) and for distant parts of the world due to long-distance transport (e.g. Carmichael et al., 1998; Liu et al., 2005). Projections of future emissions of most air pollutants in China suggest continued increases (e.g. van Aardenne et al., 1999), which will place increasing significance on the development of control strategies.

Guangdong province is situated in the coastal area of South China. It has experienced astonishing economic development and urbanization in the past two decades. The well-known development zone, the Pearl River Delta (PRD), is located at the center of Guangdong province and includes the mega-cities of Hong Kong, Guangzhou, Shenzhen, as well as several mid-size cities. Large emissions of sulfur dioxide (SO$_2$), nitrogen oxides (NO$_x$) and volatile organic carbons (VOCs) result in high O$_3$ levels and poor visibility in this region (Wang et al., 1998, 2001a; Lee and Sequeira, 2001). The NO$_x$ concentrations in Guangdong province have remained the highest in China since 1985. Currently, O$_3$ is one of the key pollutants in the atmosphere in this region (Wang et al., 2003b).

In recent years, the provincial government has made efforts to control air pollution in the province. SO$_2$ and PM10 concentrations have decreased steadily in the past decade due to the policies aimed at total emission control. However, an increasing trend of NO$_x$ and VOC concentrations has been observed in association with the rapid development of transportation and industry in the PRD region. It is expected that the corresponding photochemical smog pollution will become more and more serious in this region. This poses a challenge in the development of an optimal control strategy.

While air pollution problems have been extensively studied in Europe and the USA for decades, attention to the problems in the PRD is recent (within the last ten years). For example, Wang et al. (2003a,b) reported the chemical characterization of the boundary layer outflow of air pollution to Hong Kong during the TRACE-P (transport and chemical evolution over the Pacific) and ACE-Asia (aerosol characterization experiment-Asia Pacific region) intensive experiments in the spring of 2001. Temporal variability and emission patterns of pollution plumes in the PRD have also been investigated. Chan and Chan (2000) described enhanced O$_3$ concentrations in spring and autumn. Lam et al. (2001) found that the O$_3$ maximum was attributed to the long-range transport of high O$_3$ precursors within the polluted continental air masses as well as the photochemical buildup in dry sunny weather conditions in the low latitude regions. Kok et al. (1997) and Wang et al. (2001a) also found large ratios of CO/NO$_x$ and SO$_2$/NO$_x$ in the western area of Hong Kong, suggesting the importance of transport of regional pollution. Although many studies have been conducted on this issue, source contribution and O$_3$ chemistry are not well understood in this region.

Although several studies have been conducted, the contributions of various sources, and the local and regional contributions, remain poorly characterized. Current government plans call for the continued development of the PRD, placing further pressure on the air quality of the region. In this study, the present and possible future air quality in Guangdong province is investigated. A nested transport model, STEM-2K1(Tang et al., 2003a,b; Carmichael et al., 2003a,b), is used to analyze the current impacts of emissions from transportation, industry and power generation on Guangdong air quality. Surface measurements of O$_3$, CO, NO, NO$_2$ and SO$_2$ concentrations during March 2001 at Hok Tsui (HK, a non-urban site in Hong Kong) and Luhu (GZ, an urban site in Guangzhou) are analyzed to help compare and contrast the air quality in the PRD, assess the contribution of local and regional sources, and evaluate the simulated distributions. The model is then used to evaluate the relative importance of different sources on regional air quality. Sensitivity studies are performed that isolate the contributions from emissions transport, industry and power generation, using current estimates of emissions. Additional simulations are performed exploring possible future scenarios. These include the assessment of further growth in emissions in these sectors on regional air quality.

2. Descriptions of measurement sites and model system

2.1. Measurement sites

Measurement data from HK and GZ monitoring sites are used in this study. The HK site (22.2’N, 114.3’E), established by the Hong Kong Polytechnic University, is located on the southeastern tip of Hong Kong Island. A detailed description of the site and its surroundings is given by Wang et al. (2001a). Briefly, the site was selected to reflect atmospheric transport and conversion processes in a relatively clean area of Hong Kong. This site is located ~20 km away from the city center and
downwind of the city under the prevailing east-northeast flows in spring. The GZ station (23.16°N, 113.28°E) was set up by the Guangzhou Environmental Monitoring Center as a national control site. This site is located at the northern portion of Guangzhou and represents the urban/suburban situation. The measured trace gases are \( \text{NO}_x \), CO, SO\(_2\), O\(_3\) and NO at HK, and NO\(_x\) (NO + NO\(_2\)), CO, SO\(_2\), O\(_3\) and NO at GZ. Here, NO\(_x\) at HK includes NO, NO\(_2\) and NO\(_z\) (PAN, HONO, HNO\(_3\), N\(_2\)O\(_5\), and organic nitrates).

2.2. Model system

The STEM-2K1 nested regional chemical transport model (Tang et al., 2003a, b; Carmichael et al., 2003a, b) was used to analyze the current impacts of emissions from transportation, industry and power generation on Guangdong air quality. The model includes the SAPRC-99 gaseous mechanism (Carter, 2000), with photolysis rates calculated using the online TUV model (Madronich and Flocke, 1999). Daily TOMS (total ozone mapping spectrometer) data were used to calculate the model's overtop O\(_3\) column in the photolysis calculations. The primary domain for STEM-2K1 covers most of China and the western Pacific with a 54 km horizontal resolution. To better reflect the influence of local sources, such as power plants and urban plumes, a higher resolution is necessary. A nested domain with a nesting ratio of 1:3 was used (18 km horizontal resolution). The simulation domains are shown in Fig. 1. The NCAR/Penn State Fifth-Generation Mesoscale Model (MM5) was run in these two domains to produce the meteorological fields needed to drive STEM-2K1. The NCEP-NCAR reanalysis data (Kistler et al., 2001) were used to drive MM5.

The anthropogenic emissions used in the analysis were based on the estimates of Streets et al., (2003). Estimates of emissions from individual sectors (i.e., industry, power, domestic, transportation and shipping) are included in the analysis. Measurements obtained during the NASA TRACE-P experiment (during February–April 2001) were used in conjunction with regional modeling analysis to evaluate emission estimates for Asia (Carmichael et al., 2003a, b). It was found that the emission inventories were of sufficient quality to support preliminary studies of O\(_3\) production. Biomass burning emission (from open burning) for southeast Asia were based on the March averaged estimates for the year 2001 (Woo et al., 2003). Biogenic emissions came from GEIA (Guenther et al., 1995). The emissions were gridded based on the methodology described in Woo et al. (2003). Fig. 1 shows the spatial distribution of NO\(_x\) emissions in the two domains. The effect of resolution on the emission intensity is clearly shown. For example, the NO\(_x\) emissions over Hong Kong are around 30 mole hr\(^{-1}\) km\(^{-2}\) in the domain of the 54 km resolution, while it is over 100 mole hr\(^{-1}\) km\(^{-2}\) in the domain with 18 km resolution.

3. Results and analysis

3.1. Observed concentrations

The pollution levels in the region are illustrated by examining ambient observations from two stations.

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**Fig. 1.** Anthropogenic NO\(_x\) emissions (mol\(^{-1}\) hr\(^{-1}\) km\(^{-2}\)) for the 54 and 18 km domains.
Fig. 2 compares the observed data in HK (rural location) and GZ (urban location). Although the primary pollutants (SO$_2$, NO$_x$, and CO) show enhanced levels during daytime and strong diurnal variation at both the sites, the mixing ratios of the primary pollutants at GZ are much higher than at HK. For example, the averaged SO$_2$ and CO concentrations at GZ are 7 and 3 times those at HK, respectively, reflecting the contributions of emissions from the nearby urban sources. O$_3$ mixing ratios at both sites show a diurnal cycle with a morning low and an afternoon peak, features indicative of a strong photochemical formation during daytime. O$_3$ shows a broad maximum with average mixing ratios greater than 45 ppbv during afternoon at HK, whereas lower mixing ratios and a narrower peak at GZ. The GZ site reflects a larger impact from local and urban emissions as indicated by the larger maximum difference between daytime and nighttime O$_3$ (23.8 at GZ compared to 18.5 ppbv at HK), and the lower nighttime values at GZ (5 vs. ~30 ppbv at HK). The different diurnal cycles at the two sites reflect different emission influences.

The slopes of observed CO vs. NO$_x$ (NO$_y$) and SO$_2$ vs. NO$_x$ (NO$_y$) at the two sites provide useful information to compare regional emissions and to provide insight into dominating source sectors (see Fig. 3). The SO$_2$/NO$_x$ slope at HK is 0.2 ppbv ppbv$^{-1}$, in comparison to the SO$_2$/NO$_y$ slope at GZ of 0.44 ppbv ppbv$^{-1}$ ($r^2$ values were 0.63 and 0.67, respectively). The CO/NO$_x$ slope at HK is 6.3 ppbv ppbv$^{-1}$, whereas the slope for CO/NO$_y$ at GZ is 11.9 ppbv ppbv$^{-1}$ (with $r^2$ of 0.18 and 0.44, respectively).

These observation-based (OB) ratios can also be compared to ratios derived from the emission inventories. The SO$_2$/NO$_x$ emission-based (EB) ratio is 0.84 ppbv ppbv$^{-1}$ for Guangdong province and 0.51 ppbv ppbv$^{-1}$ for Hong Kong. For CO/NO$_x$, the EB ratio is 14 ppbv ppbv$^{-1}$ for Guangdong, compared to a much lower ratio of 1.4 ppbv ppbv$^{-1}$ for Hong Kong. (Please note that NO$_x$ represents a small contribution to NO$_y$ at HK. Thus NO$_y$ provides a good surrogate for emitted NO$_2$. In contrast, at GZ, most of the NO$_y$ is in the form of NO$_x$. Therefore, these different ratios using NO$_x$ and NO$_y$ can be compared to emission estimates.) In the case of SO$_2$ and NO$_x$, the behavior of OB ratios is the same as that of the EB ratios, with GZ ratios higher than the HK ratios. However, the OB ratios are ~50% smaller than the EB values. For CO/NO$_x$, the OB ratios are consistent with the EB ratios in terms of GZ being greater than those for HK. But while the GZ OB value is within 10% of the EB value, at HK the OB value is an order of magnitude higher than the EB value. The model-simulated CO/NO$_x$ ratio for HK was 6.6 ppbv ppbv$^{-1}$, which is close to the observed ratio at HK. This suggests a significant contribution to sources outside of the Hong Kong region. The low correlation coefficient of CO vs. NO$_x$ (compared with SO$_2$ vs. NO$_x$) also indicates a mixing of individual plumes with different emission ratios.

As discussed by Wang et al. (2003b), the rural HK site can be influenced by urban plumes, as indicated by
sharp rises in the time series of hourly averaged mixing ratios of CO, SO$_2$, NO$_x$, and O$_3$ (Fig. 4). March is a transitional period between winter and summer monsoons. The Siberian high systems and the Pacific high systems come and go in this region (Bey et al., 2001; Wang et al., 2003a) which result in large day-to-day variations in the trace gas levels. Several peaks during this month are shown in Fig. 4. For example, from 18 to 23 March (Julian days 77–82) there was a sharp rise in the mixing ratios of CO, SO$_2$ and NO$_x$ and a corresponding decrease in O$_3$. On 18 March, an intense high pressure system moved over south China causing a
surge of cold weather in Hong Kong, and these air masses had elevated levels of CO, SO$_2$ and NO$_y$. The influences of urban plumes on this site are also shown. During 20–21 March, a high-pressure system moved slowly from south China to Hong Kong, and it was sunny and a sea–land breeze developed. The maximum values of CO, SO$_2$ and NO$_y$ were observed on 21 March due to the pollutants recirculating under this sea breeze. O$_3$ formation was suppressed in this plume as shown by the low O$_3$ values. During 22–23 March, a sustained southerly air flow brought in marine air masses from the South China Sea, and this resulted in a drop in the mixing ratios of CO, SO$_2$ and NO$_y$.

### 3.2. Model results

The emission inventories used in this study were evaluated using the TRACE-P aircraft data by Carmichael et al. (2003a, b). They found that the emission inventories were of sufficient quality to produce predicted concentration fields that were in semi-quantitative agreement with the observations for many species. Here, we compare the model predictions with the surface observations. The simulated values at HK for the 18 km and 54 km runs are shown in Fig. 4. The simulations are able to capture many of the observed features. For example, the increase in CO, SO$_2$ and NO$_y$ during 19–22 March is captured in the simulations. However, the model also clearly underestimates the magnitude of the peak values. The peak values are better captured using the 18 km grid, showing that the refined higher-resolution emissions and/or meteorology are able to resolve the differences among urban, suburban and rural areas better. The modeled O$_3$ values are not sensitive to grid resolution. Furthermore, the model captures the peak O$_3$ behavior, but systematically overestimates the low values. These results may imply that the 18 km-model resolution is still too coarse to capture the distinct plumes of very high NO$_y$ that are correlated with low O$_3$. The scatter plots of observed vs. simulated SO$_2$ and NO$_y$ at HK (Fig. 5) also show that the results from fine resolution have higher correlation coefficients and (model)/(obs.) ratios closer to unity. Tang et al. (2003a) also tested the multi-scale simulation using nested domains in the eastern Pacific and found that the fine resolution can better reflect the urban plume structures.

As discussed previously, the model is able to predict many of the important observed features for the major species including SO$_2$, NO$_x$ and O$_3$. To gain insights into the regional distribution of pollutants, the monthly averaged concentration distributions of CO, SO$_2$, NO$_x$, VOC, O$_3$ and NO$_y$ (NO$_y$–NO$_x$) at the lowest model layer (37.5 m) for the 18 km domain are shown in Fig. 6. The distributions of the primary pollutants (CO, SO$_2$, NO$_x$ and VOC) show features that are similar to the emission patterns. The concentrations are highest in and around Guangdong, Guangzhou and Hong Kong, where averaged CO, SO$_2$, NO$_x$ and VOC concentrations exceeded 550, 25, 25 and 18 ppbv, respectively. The average CO concentration in Guangdong is lower than that in Hunan, Jiangxi and Fujian provinces and higher than in Guangxi province. The average SO$_2$ and NO$_x$ concentrations in Guangdong are higher than in the surrounding provinces, while the average VOC concentration in Guangdong is lower than in Hunan and Jiangxi provinces and comparable with that in Fujian and Guangxi provinces.

O$_3$ and NO$_y$ are secondary pollutants that are influenced by chemical formation and transport. Fig. 6E shows that O$_3$ concentrations are the highest in the eastern and northern portions of the domain, and that O$_3$ values are decreased as air is transported over the high NO$_x$ emissions region around Hong Kong and Guangdong.
3.3. Contribution of different sources

As discussed in Section 3.2, the air quality problem in Guangdong province in spring is characterized by periodical high concentrations of O₃ and its precursors induced by strong regional emissions and suitable synoptic conditions. An important question of interest to air quality management in the region is the relative contributions of different emission sources to the local and regional air quality. In order to reveal the impacts of

Fig. 6. Calculated monthly averaged surface concentration distributions (ppbv) during March 2001. (A) CO, (B) SO₂, (C) NOₓ, (D) VOC, (E) O₃, (F) NO₂.
different anthropogenic sources on the air quality in Guangdong province, three case studies were performed to isolate the influence of power generation, transportation and industry sources. In each case, the target sources in Guangdong province were switched off, and the influence of the target sources on regional air quality were obtained from the difference between the base case and the control case. Table 1 summarizes the contribution of these three source sectors to the emissions and average ambient levels in Guangdong province. Here the percent concentration contribution refers to the difference between the base case and control case divided by the base case \(( \times 100)\). It should be noted that the background concentrations of each species are excluded in the base case. In the case of \(O_3\), averaged 2:00 p.m. (local time) values are used in the base and the control cases to reflect the impacts of different emission sources on \(O_3\) production.

Power generation has the largest contribution to \(SO_2\) emissions (accounting for 47.3% of the total) and has a very small contribution to CO. The contribution of industrial sources to \(SO_2\) and CO is 43.0% and 20.6%, respectively. The transportation sector has the lowest contribution to \(SO_2\) (3.6%) and the highest contribution to CO (65.5%). The contributions of the various source sectors to the average concentration distributions are presented in Figs. 7–9 (Here, the background concentrations of each species are included in the base case, so the concentration contribution fractions are small compared with Table 1). For \(SO_2\), the emissions from power generation and industry are of similar magnitude, but the distributions are different. Power generation has its greatest influence in the region in the Shaoguan and Guangzhou corridor where large power plants are located, while the influence of industry sources is largest in the eastern and western parts of Guangdong province.

In the western regions (downwind during spring), the contributions of power and industry are both large. The contributions from the transportation sector to \(SO_2\) have a similar distribution to that for industry, but the magnitude is much smaller.

For \(NO_x\) and \(VOC\), the transportation sector is the largest source and accounts for 49.2% and 68.0% of the total anthropogenic emissions, respectively. In the case of \(NO_x\), the power and industrial sectors contribute ~20% and 15%, respectively. The influence range of the transportation sector to \(NO_x\) and \(VOC\) levels is large and covers most of the eastern and western Guangdong province. The contributions from industrial sources show three influence centers which are located in Huizhou (east of Guangdong), Guangzhou (center of Guangdong) and Zhanjiang (southwest of Guangdong). The contributions due to power generation are clearly seen around the large point sources.

The contribution of the transportation sector to ambient \(O_3\) is the largest, accounting for 17.8%, compared with industrial sources 6.4% and power generation 6.7%. The impact of the transportation sources on \(O_3\) covers most of the area of Guangdong, while that due to industry sources is concentrated in the central areas of Guangdong. The influence of power generation on \(O_3\) concentration is mainly limited to the northeast regions of Guangdong. Smaller \(O_3\) enhancements due to the transportation and industry sources are found in the center of Guangdong and these regions correspond to higher \(NO_x\) source regions.

### 3.4. Scenario analysis and implication for control strategy study

In recent years the local government has made significant efforts to control air pollution in Guangdong

<table>
<thead>
<tr>
<th>Source</th>
<th>Emission</th>
<th>Power plant</th>
<th>Transportation</th>
<th>Industry</th>
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</thead>
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<td>(SO_2)</td>
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<td>3.6</td>
<td>43.0</td>
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<tr>
<td>Concentration</td>
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<td>2.6</td>
<td>30.0</td>
<td></td>
</tr>
<tr>
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<td>49.2</td>
<td>20.0</td>
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<tr>
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<tr>
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<td>Concentration</td>
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<tr>
<td>(O_3)</td>
<td>Concentration</td>
<td>6.7</td>
<td>17.8</td>
<td>6.4</td>
</tr>
</tbody>
</table>

\[a\]The three sectors shown in this table do not account for 100% of the anthropogenic emissions. The contributions from domestic and shipping sectors are not shown, and account for the differences.
province. Ambient SO$_2$ and PM$_{10}$ concentrations have decreased steadily due to new emission control policies. However, NO$_x$ and VOC concentrations have continued to rise due to the continued rapid development of transportation and industry in the PRD region. As a result, the photochemical smog is expected to increase. From the studies discussed in the last section, the transportation and industrial sectors were found to be the most important in terms of ambient O$_3$. Furthermore, according to the energy plan for the next two decades for Guangdong province, the main energy consumption is expected in the industry and transportation sectors. To explore possible impacts of continued growth in these sectors on air pollution levels, two scenarios were studied, in which the emissions from transportation and industry sources were doubled.

Figs. 10–11 shows the difference in monthly mean concentrations (double case—base case) of SO$_2$, NO$_x$, VOC and O$_3$ for the two scenarios. Generally, for the primary pollutants (SO$_2$, NO$_x$, and VOC), the increases in ambient levels due to transportation sources are felt throughout the domain, whereas the increases due to industry sources are concentrated over the Guangzhou and Huizhou areas. For SO$_2$, the doubling of emissions from industry has a much larger effect on ambient levels. In terms of O$_3$, the increase in the transportation sector sources has the largest impact (~twice the effect of the industrial sector), with mean values increased by more than 4 ppbv over most of the domain.

Since the transportation sources play a critical role in future O$_3$ levels in the PRD region, the relative importance of its precursors (NO$_x$ and VOC) in O$_3$ production was examined to provide insights into possible control strategies. Additional simulations were performed where NO$_x$ and VOC emissions from...
transportation sources were doubled separately to see how \( \text{O}_3 \) concentrations respond. The percentage changes in \( \text{O}_3 \) are shown in Fig. 12. The doubling of \( \text{NO}_x \) emissions leads to \( \text{O}_3 \) enhancements in non-urban areas and \( \text{O}_3 \) reductions in urban areas, indicating that non-urban areas are \( \text{NO}_x \)-limited (i.e. \( \text{O}_3 \) increases when \( \text{NO}_x \) emissions increase) and urban areas are VOC-limited. These results provide useful information for \( \text{O}_3 \) control in the region. If \( \text{O}_3 \) abatement in urban areas is the target, then reduction in VOC emissions is necessary. On the other hand, if we focus on \( \text{O}_3 \) levels in non-urban areas, then \( \text{NO}_x \) reduction is needed.

The \( \text{O}_3/\text{NO}_x \) ratio can be regarded as an index to help identify \( \text{NO}_x \)-limited and VOC-limited regimes in \( \text{O}_3 \) photochemical production. From these simulations, a threshold for the \( \text{O}_3/\text{NO}_x \) ratio was found to be around 25 ppbv ppbv\(^{-1}\). If the \( \text{O}_3/\text{NO}_x \) ratio is greater than 25, a VOC-limited regime is expected, otherwise it is \( \text{NO}_x \)-limited. It is important to note that the absolute transition value for this ratio is uncertain and further studies are required to quantify it better. Model resolution is one issue that can influence such an analysis. Tunis (http://www.emep.int/reports/DNMI_NOTE_2_2001.pdf) found, based on model calculations with grid resolutions from 50 to 4 km, that there is a tendency of coarser resolutions to underestimate the intensity of the VOC-sensitive regime and to overestimate the intensity of the \( \text{NO}_x \) reductions. The spatial distribution of the \( \text{O}_3/\text{NO}_x \) ratio helps identify \( \text{NO}_x \)-limited or VOC-limited regions, which is of practical significance for regional \( \text{O}_3 \) control. Thus, additional studies are needed at finer resolution than those presented here to more precisely determine the effects of \( \text{NO}_x \) and VOC controls.
4. Summary and conclusion

This study was concerned with air quality situations in the PRD region, Guangdong province, China, during March 2001. The focus of the study was on the role played by local emissions on the concentrations of O₃, CO, NO, NOₓ, and SO₂ in Guangdong province. Analyses were focused on evaluating the importance of emission sources from transportation, industry and power generation on regional air quality. Furthermore, the relative importance of NOₓ and VOC emissions from the transportation sector for O₃ production was examined in order to provide guidance on control strategies for reduction of photochemical smog in the region. Based on the observational data and modeling results, the following conclusion can be drawn:

(1) The observed concentrations of O₃, SO₂, NOₓ(NOₓ), and CO at the urban site clearly differ from those at the rural site in terms of their means, diurnal cycles and the ratios of CO/NOₓ and SO₂/NOₓ. These differences mainly reflect the impact from local emissions.

(2) The control simulation with all emissions included shows a fairly satisfactory performance of the model in terms of the comparison between the observed and modeled concentrations of CO, SO₂, NOₓ and O₃, although the observed extremes are less well simulated. This gives us confidence in carrying out the sensitivity studies using various scenarios.

(3) Three simulations with different emission scenarios were performed to examine the relative contribution of different types of sources on the regional air quality. The results suggest that the transportation source was the main contributor to NOₓ, CO and O₃ concentrations in Guangdong province, accounting for 34.2%, 33.1% and 17.8% of their total concentrations, respectively. For SO₂ concentration,
the main contributor is the power plant source with a contribution rate of 32.9%.

(4) While the increases in ambient levels of SO$_2$, NO$_x$, and VOC due to increased transportation sources are felt throughout the domain, the increases due to increased industrial sources are concentrated over the Guangzhou and Huizhou areas, which reflect the different characteristics of the two emission sources. For SO$_2$, the doubling of emissions from the industry has a much larger effect on the ambient levels than the doubling from the transportation, whereas the increase in the transportation sector sources has approximately twice the effect of the increased industrial emission on O$_3$.

(5) The scenario analysis indicates that doubling of both emissions from the transportation and industry sources will increase the O$_3$ concentration about 26.7% and 8.5% for the whole region, with the influence from the transportation sources stronger than those from the industry sources.

(6) The O$_3$/NO$_x$ ratio of 25 was found to be a reasonable threshold to separate NO$_x$-limited and VOC-limited regimes concerning O$_3$ chemistry. The sensitivity studies indicate that the urban area is VOC-limited and the non-urban area NO$_x$-limited. These results have implications for O$_3$ control strategy in the target region.

The management of air quality in the PRD presents a formidable challenge, in light of the expected continued increase in economic development in the region. Air quality models have an important role to play in air quality management in the region. The results presented here need to be extended to the high O$_3$ periods and continued development and improvements in regional emission estimates are needed. Efforts in these directions are going on.

Fig. 10. Monthly mean concentration differences (double case-base) (ppbv) after doubling transportation sources. (A) SO$_2$, (B) NO$_x$, (C) VOC, (D) O$_3$. 
Fig. 11. Monthly mean concentration differences (double case-base) (ppbv) after doubling industry sources. (A) SO$_2$, (B) NO$_x$, (C) VOC, (D) O$_3$.

Fig. 12. Average O$_3$ change after doubling NO$_x$ from transportation sources (left). O$_3$ difference from doubling NO$_x$ and VOC from transportation sources separately, plotted against O$_3$/NO$_x$ (right).
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