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Feasibility and difficulties of China's new air quality standard compliance: PRD case of $PM_{2.5}$ and ozone from 2010 to 2025

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Abstract. Improving the air quality in China is a long and arduous task. Although China has made very aggressive plans for air pollutant control, the difficulties in achieving the new air quality goals are still significant. A lot of cities are developing their implementation plan (CIP) for new air quality goals. In this study, a southern city, Guangzhou, has been selected to analyze the feasibility and difficulties of new air quality standard compliance, as well as the CIP evaluation. A comprehensive study of the air quality status in Guangzhou and the surrounding area was conducted using 22 monitoring sites collection data for O_3, $PM_{2.5}$ and PM_{10}. The monthly non-attainment rates for O_3 vary from 7 to 25 % for May to November. The city average $PM_{2.5}$ concentration was 53 $\mu g\,m^{-3}$ in Guangzhou in 2010, which needs to be reduced by at least 34 % to achieve the target of 35 $\mu g\,m^{-3}$. The $PM_{2.5}$ high violation months are from November to March. A CIP was developed for Guangzhou, which focused on $PM_{2.5}$. Based on the CIP, the emission amounts of NO_x, PM_{10}, $PM_{2.5}$ and volatile organic compounds (VOCs) in 2025 would be controlled to 119, 61, 26 and 163 thousand tons, respectively, reduced by 51.9 %, 55.9 %, 61.8 % and 41.3 %, respectively, compared to 2010. Analysis of air quality using the model MM5-STEM suggests that the long-term control measures would achieve the $PM_{2.5}$ and PM_{10} goals successfully by 2025. The $PM_{2.5}$ annual average concentration would be reduced to 27 $\mu g\,m^{-3}$ in 2025. However, such $PM_{2.5}$-based emission control scenarios may enhance the ozone pollution problems. The O_3 non-attainment rate would increase from 7.1 % in 2010 to 12.9 % in 2025, implying that ozone will likely become a major compliance issue with the new national ambient air quality standards (NAAQS). This suggests that O_3 control must be taken into account while designing $PM_{2.5}$ control strategies, especially $PM_{2.5}$ compliance under increased atmospheric oxidation, and for VOCs / NO_x reduction ratios need to be further investigated, in order to eventually achieve O_3–$PM_{2.5}$ co-improvement in this region or other cities.

1 Introduction

To safeguard a healthy, comfortable and safe atmospheric environment where the masses live, China has to change its thinking about air pollution control. It must identify compliance with air quality standards as the core and the ultimate management goal, and tackle the emission reduction of fine particle ($PM_{2.5}$) and related precursors as an important means to improve air quality. China launched a program for the prevention and control of air pollution in the 1970s. Since then, the emphasis has been put on the emission intensity of key pollution sources and the total emissions of major pollutants, rather than ambient air quality (Y. Wang et al., 2013; Xing et al., 2011; Yan and Crookes, 2009; Schreifels et al., 2012; Xue et al., 2013; Geng and Sarkis, 2012; Zhao et al., 2013). Targets of atmospheric pollutant emission reduction are primarily based on emission reduction technologies

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and economic potential, rather than on the requirement of human health related to air quality. Air quality assessment has traditionally taken into account three "traditional" atmospheric pollutants, SO_2, NO_2 and PM_{10}, instead of $PM_{2.5}$ and O_3, both of which have a more severe impact on human health. As China marches on the path to a well-off and modernized society, its people, especially those in cities that are concerned about human health hazards associated with air pollution, are demanding greater attention be given to ambient air quality problems. China finalized a new version of the national ambient air quality standards (NAAQS) in 2012 (GB3095-2012). The previous environmental air quality standard had been in place since 2000. In this revision, $PM_{2.5}$ and O_3, having an important impact on human health, are placed in a core position in the prevention and control of air pollution. The annual standard for $PM_{2.5}$ was set at 35 $\mu g\,m^{-3}$ for the first time. The ozone standard was revised from a 1 h average of 0.2 $mg\,m^{-3}$ only to an 8 h average of 0.16 $mg\,m^{-3}$. The NAAQS, with reference to the World Health Organization (WHO) air quality standards, has introduced a stricter limit for PM_{10} and NO_2 for the annual average, so that the PM_{10} and NO_2 standards are in line with the WHO Phase 1 target for air quality improvement.

Although $PM_{2.5}$ monitoring had not been introduced in most cities in China before the new NAAQS, the environmental monitoring data for SO_2, NO_2 and PM_{10} indicate that the urban air quality remains much worse than the standards for a well-off and modernized society. According to the atmospheric environmental monitoring data in 333 cities at the prefecture level or above in China, the annual mean concentration of SO_2, NO_2 and PM_{10} in prefecture-level cities was 35 $\mu g\,m^{-3}$, 28 $\mu g\,m^{-3}$ and 79 $\mu g\,m^{-3}$, respectively, in 2010. Even with the $PM_{2.5}$ pollution not taken into consideration, as many as 216 cities cannot meet the standards, accounting for 2/3 of the total number of cities (Hao et al., 2012). In China, especially the northern part, $PM_{2.5}$ and PM_{10} are still far beyond the standards (Gao et al., 2011). The data on air pollution for the first six months in 2013 were released by MEP recently (Index: 000014672/2013-01270, www.zhb.gov.cn). The average concentration of $PM_{2.5}$ (PM_{10}) was 115 (193) $\mu g\,m^{-3}$ in the Beijing–Tianjin–Hebei (BTH) region. According to the new NAAQS, no city meets either $PM_{2.5}$ or PM_{10} standard in this region. The Yangzi River Delta (YRD) region reported 69 (103) $\mu g\,m^{-3}$ $PM_{2.5}$ (PM_{10}) concentrations, while the Pear River Detlta (PRD), which is near Hong Kong, has a lower concentration of about 44 (64) $\mu g\,m^{-3}$ (Peng et al., 2011). A satellite-derived $PM_{2.5}$ distribution shows that the $PM_{2.5}$ concentration in eastern China is 70–100 $\mu g\,m^{-3}$ (Donkelaar et al., 2010). The ozone non-attainment rate (maximum 8 h average concentration) was 5.0–33.7 %, 2.2–27.1 % and 5.5–15.5 % in BTH, YRD and PRD, respectively. Besides the non-attainment rate, the peak concentrations of ozone in the three regions are constantly high. Wang et al. (2006) reported that hourly ozone concentration of 200–300 ppbv (or 400–600 $ug\,m^{-3}$) was observed downwind of Beijing in 2005. Even after full control during the 2008 Beijing Olympics, nearly 200 ppbv was seen in Beijing (Wang et al., 2010). Other investigators also reported high ozone in Beijing and the two other regions (Geng et al., 2009; Tie et al., 2009; Liu et al., 2010; Zheng et al., 2009a, 2010).

Research needs to be developed to better understand the ability to attain the new NAAQS. The Ministry of Environment Protection (MEP) in China has required each city to prepare a city implementation plan (CIP) to achieve the new goals. However, as mentioned above, the lack of large-scale $PM_{2.5}$ monitoring before 2012 is one of the obstacles for making a CIP. Another difficulty comes from the lack of planning science and technology. Without systematic evaluations based on complex tools, it is neither possible to understand how the air quality will respond to the reduction measures nor to make a scientific strategy on air quality improvement (Zhong et al., 2013; Ponche and Vinuesa, 2005; Y. Wang et al., 2009; Karatzas et al., 2003; Zheng et al.,2009b; Lu et al., 2013). Unfortunately, the technical capability for local environmental bureaus is still not sufficient to do so. Thus, this study aims to provide an example on how to develop the CIP. In this study, we chose Guangzhou as a pilot city because the scientific $PM_{2.5}$ and O_3 monitoring network was already set up and providing data ahead of other cities (Yuan et al., 2012; Liu et al., 2013; Chan and Yao, 2008; Tan et al., 2009; Verma et al., 2010). The successful regional cooperation between the governments in Guangdong and Hong Kong helps the understanding of the $PM_{2.5}$ and ozone status, which are very much regional in nature. The regional collaborative efforts on joint air quality management include establishing the first PRD regional air quality monitoring network since 2005 to provide high-quality air pollution data and publishing data, which has been otherwise under tight scrutiny in the past (Zhong et al., 2012). On the other hand, Guangzhou is representative of much of China since the Asian Games in 2010 demonstrated the difficulty in reducing $PM_{2.5}$ and O_3 concentrations. Guangzhou made great efforts in controlling emissions during the Asian Games. Although the SO_2, NO_2, volatile organic compound (VOC) and dust control measures have significantly reduced pollutant emissions, the ambient $PM_{2.5}$ and ozone pollution were not significantly improved during the Asian Games, indicating that secondary pollution alleviation should be based on a long-term, comprehensive abatement strategy. Thus, a study focusing on the future trend and target achievement strategy is essential to improving the air quality. This experience could be a lesson for all China cities that a long-term, well-organized emission control plan should be developed to control $PM_{2.5}$ and ozone.

Our objective is to provide a full review on identifying the likelihood and difficulties in meeting the new NAAQS considering the air quality starting point and emission reduction potential of a region. Here we examined the air quality status in PRD by focusing on three pollutants: O_3, PM_{10} and $PM_{2.5}$ collected from the national and local monitoring sites

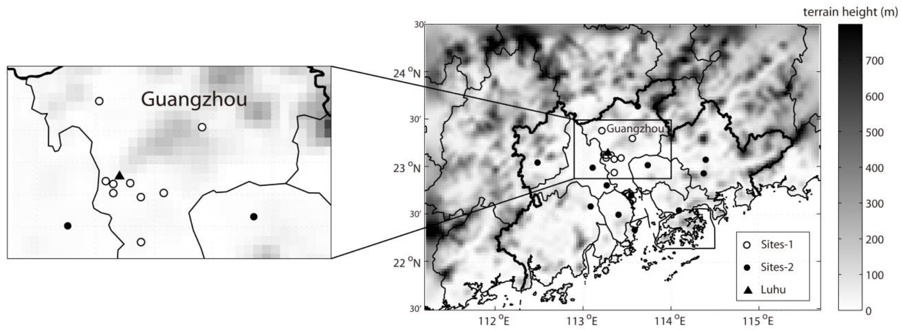

Fig. 1. Geographical map of the Pearl River Delta region and location of air quality monitoring sites. (Sites-1: sites from Guangzhou National Control Network; Sites-2: sites from PRD Regional Air Quality Monitoring Network; Luhu: Luhu site.)

in 2010. We compared total emission amounts in 2010 and 2025 in order to assess the ability of pollution control in the 12th, 13th and 14th five-year plans (FYPs). In addition, air quality simulation in 2025 was conducted and then compared to NAAQS to infer the impact of the emission control plan and to evaluate the accessibility of the new NAAQS. This paper is organized as follows: air pollution status, emission controls, air quality improvements, remaining problems and potential solution.

2 Air pollution status

Observation data in 2010 were extracted from two sources: (1) 13 sites located in PRD from the PRD Regional Air Quality Monitoring Network, which was jointly established by Guangdong Provincial Environmental Monitoring Center (GDEMC) and the Environmental Protection Department (HKEPD) of the Hong Kong Special Administrative Region (HKSAR); and (2) 10 sites from the Guangzhou (GZ) National Control Network, which was set up by the GDEMC (Fig. 1). The Luhu site in the urban area belongs to both GZ National Control Network and PRD Regional Air Quality Monitoring Network. Overall, 22 sites were chosen for this study. O_3 and PM_{10} are available at all the sites, but only 11 sites in Guangzhou provide data on $PM_{2.5}$ levels (9 sites from Guangzhou National Control Network, 2 sites from GDEMC) (X. Wang et al., 2013, 2005)

2.1 O_3

Figure 2 shows the annual highest 8 h and 1 h average ozone in the region for each site in 2010. Sites in central Guangzhou were highlighted on the left. The stations with O_3 concentrations lower than the standard are denoted by pink dots, while the other colored dots represent the non-attainment areas. For both statistics, the highest O_3 values are in southern Guangzhou, along the Guangzhou–Foshan and Guangzhou–Zhongshan boundary. The highest 8 h average ozone concentration is 350–390 $\mu g\,m^{-3}$, which is higher

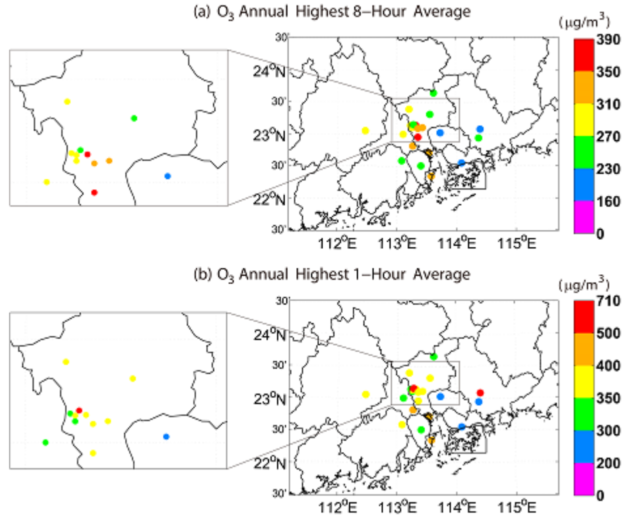

Fig. 2. Ozone concentration ($\mu g\,m^{-3}$) at each of the 22 individual sites in PRD region in 2010 of **(a)** the annual highest daily maximum 8 h average and **(b)** the annual highest 1 h average.

than the limit of 160 $\mu g\,m^{-3}$. Most sites located along the southwest Guangzhou boundary bear the highest 8 h concentration of 270–350 $\mu g\,m^{-3}$. The highest 8 h ozone concentration in eastern PRD is lower than in the west, though all the highest 8 h values are still above the national standard, as denoted by the blue, green, yellow, orange, and red dots. The annual highest 1 h ozone concentration exceeds 500 $\mu g\,m^{-3}$ in Guangzhou and Huizhou, higher than in other cities.

In addition to the highest concentration distribution, an alternate type of statistic used to analyze exceedances of the ozone air quality standard is the frequency of occurrence of daily maximum 8 h average concentrations in excess of the standards (Fig. 3). The inter-month non-attainment rate variation is provided for all sites in the PRD and for sites in Guangzhou and Foshan (GZ & FS), representing the heavily polluted areas, and sites in surrounding areas. For each

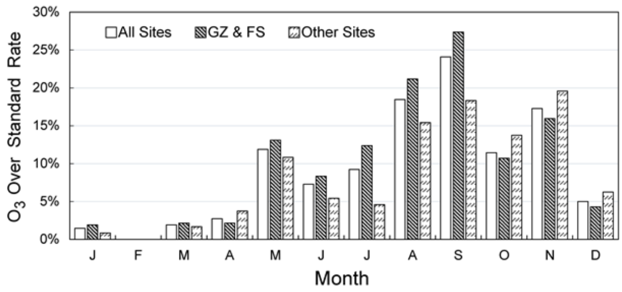

Fig. 3. Average fraction of days per month whose daily maximum 8 h average exceeds 160 $\mu g\,m^{-3}$ out of all days per month with ozone data in 2010.

month, the fraction of exceedance days out of all days with data was calculated for each site as the over-standard rate. The resulting values for each month were then averaged across all sites in each of the three ranges as discussed above.

Overall, the number of O_3 non-attainment days increases in summer and decrease in winter in this region. The monthly non-attainment rates for O_3 varied from 7 to 25 % from May to November in 2010. We found that 79 % of all the exceedances at all sites occur in summer and fall (June–November). The fraction of non-attainment in the Guangzhou and Foshan city regions is as high as 80 % of the days. A low non-attainment rate was observed in October in Guangzhou and Foshan, which also contribute to the low non-attainment rate in the whole region in October. As summarized in a previous study, a strict emission control plan was implemented in Guangzhou in October 2010; e.g., large point sources were required to reduce their emissions by 30 % (Liu et al., 2013; Zhong et al., 2013). These measures may contribute to the low ozone concentration in cities in this month particularly. Compared with the Guangzhou and Foshan urban areas, the surrounding area has significantly lower O_3 concentrations from May to September.

2.2 PM_{10}

The highest daily average, annual PM_{10} concentration and non-attainment rate were applied to describe the PM_{10} pollution status (Fig. 4). The highest PM_{10} daily average concentration in Guangzhou is significantly lower than in the surrounding areas: Foshan, Zhongshan, western Dongguan and Shenzhen (Fig. 4a). In Zhongshan and Shenzhen, the highest daily PM_{10} concentrations are 400 $\mu g\,m^{-3}$ and above. This observation is consistent with our previous study, that the PM_{10} was influenced a lot by local contributors (Liu et al., 2013). Dust control measures contribute a constant reduction to the highest PM_{10} level in Guangzhou. The Guangzhou municipal government shut down all the construction sites and increased the frequency of watering roads from once per day to four times per day in 2010.

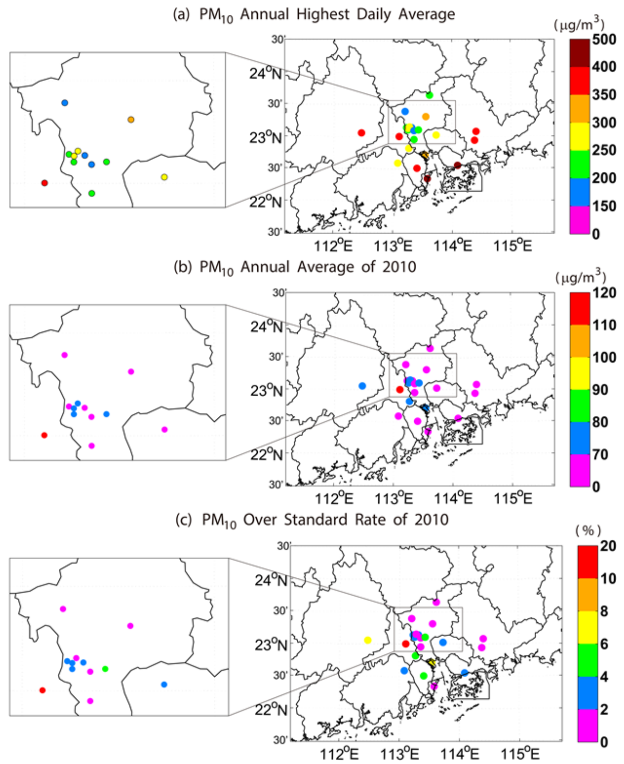

Fig. 4. PM_{10} concentration ($\mu g\,m^{-3}$) at each of the 22 individual sites in PRD region in 2010 of **(a)** the annual highest daily average, **(b)** the annual average and **(c)** non-attainment rate.

It should be noted that the new NAAQS proposes a stricter annual PM_{10} standard of 70 $\mu g\,m^{-3}$. Most of the sites reported annual averages that are lower than the limits. Some sites report the annual average between 70 and 80 $\mu g\,m^{-3}$ (Fig. 4b). With consistent control efforts, it is not difficult to reduce the annual PM_{10} concentration to meet the national standard. The highest annual average PM_{10} concentration, observed in Foshan, was above 110 $\mu g\,m^{-3}$. The non-attainment rate, based on daily PM_{10} concentrations, is also low in Guangzhou (< 2 % for most sites) in 2010 as shown in Fig. 4c. The risk of high non-attainment rates is still from the surrounding area, mainly Foshan. The monthly variations of PM_{10} and $PM_{2.5}$ are compared in the next section.

2.3 $PM_{2.5}$

Other than O_3 and PM_{10}, $PM_{2.5}$ air quality data are only available from 11 sites in Guangzhou. The highest daily average, annual average $PM_{2.5}$ concentration and non-attainment rate were applied to describe the $PM_{2.5}$ pollution status (Fig. 5). Different from PM_{10}, the need for $PM_{2.5}$ pollution control is driven by both high annual average and high daily concentrations. The annual (daily) standard for $PM_{2.5}$ was set at 35 $\mu g\,m^{-3}$ (75 $\mu g\,m^{-3}$). The annual average $PM_{2.5}$ concentration is about 35 to 63 $\mu g\,m^{-3}$ in Guangzhou, whereas

$PM_{2.5}$ can exceed 58 µg m^{-3} in industrial areas. More than that, the heavy $PM_{2.5}$ pollution days occur more frequently than PM_{10} pollution days. The non-attainment rate based on daily concentration could reach as high as 25 % and above in southern Guangzhou. The highest daily concentrations reach up to 271 µg m^{-3}. These concentrations are significantly higher than the standard recommended by international organizations and other countries (10–35 µg m^{-3}). The city average is 53 µg m^{-3} in Guangzhou in 2010. To achieve the target of 35 µg m^{-3}, the concentration reduction needs to be at least 34 %.

Monthly variation of $PM_{2.5}$ non-attainment rates is quite similar to the PM_{10} variation (Fig. 6). About 83 % of PM_{10} non-attainment days are $PM_{2.5}$ non-attainment days also. The average $PM_{2.5}$ non-attainment rate is about six times that of the PM_{10} non-attainment rate. The $PM_{2.5}$ concentration reduction will likely be effective for PM_{10} attainment, while the reverse is likely not true. The over-standard rate is calculated based on the fraction of exceedance days out of all days for each site in each month. We find that the $PM_{2.5}$ and PM_{10} concentrations have opposite seasonal variation compared with ozone. The highest non-attainment rates appear from November to March, accounting for 90 % of all the PM_{10} exceedances in all sites, 91 % in the Guangzhou and Foshan city regions, and 89 % in the surrounding area.

3 Emission controls

3.1 Targets and control principles

To meet the public's increasing expectations, the vast majority of cities in China need to achieve the ambient air quality standards in the next 15 to 20 yr. The MEP expects that more than 80 % of cities in China can achieve the air quality goals by 2025. As required by national instruction, Guangzhou, classified as a heavily polluted city, should attain the new air quality in 15 yr. Guangzhou Environmental Protection Bureau (EPB) also announced their own targets to try to achieve the $PM_{2.5}$ goal in 2020 and make sure to achieve $PM_{2.5}$ and NO_2 targets by 2025.

Emission control actions are designed based on a series clean air actions committed by local and regional authorities. Technology has a major role to play, and innovations need to be stepped up to meet the challenges (Biswas et al., 2011). The Guangzhou municipal government is planning to introduce a series of control measures in future years, giving a strong impetus to the prevention and control of atmospheric pollution. Useful experience has been accumulated from the Guangzhou Asian Games for further regional joint prevention and control of air pollution. To substantially cut down emissions of atmospheric pollutants amid stable and rapid economic expansion, it necessitates a faster slump in the emission intensity per unit of GDP than what has been accomplished in the last two decades in order to offset the negative effects of rapid GDP growth on pollution reduction. The control measures before 2012 are from "strengthened comprehensive implementation programs of prevention and control of air pollution after the Asian Games in Guangzhou", while the measures between 2012 and 2016 reference "comprehensive work plan of air pollution prevention and control in Guangzhou 2012–2016" and "Total Emission Control Plan of Major Pollutants in Guangzhou during the Twelfth Five-Year Plan Period".

The regional control is also considered in this research to provide a background emission inventory. To augment the analysis with local information, the following documents are referenced to develop the regional action plan: (1) before 2012: "Clean Air Action Plan in Pearl River Delta in Guangdong Province"; (2) from 2012 to 2020: the "Outline of the Plan for the Reform and Development of the Pearl River Delta (2008–2020)", the "Regional Cooperation Plan on Building a Quality Living Area", the "Jointly Prevention & Control of Regional Air Pollution in Pearl River Delta in Guangdong Province", as well as the "Emission Reduction Plan for 2012–2020, Committed by the Framework Agreement between Guangdong and Hong Kong Governments".

3.2 Emission forecast

Emission forecasting typically includes two parts: emission factors and activity level. A business-as-usual (BAU) scenario is set up as the first step to reflect the projection of economic development in the region with the present emission control level maintained. If no further control is taken in Guangzhou, the total emissions of SO_2, NO_x, PM_{10}, $PM_{2.5}$, and VOCs would reach 145, 361, 173, 84 and 402 thousand tons, respectively, by 2025.

The major pollution control measures include the following: (1) a series of policy measures aimed at total emission control will be implemented, such as a preferential tariff for desulfurization to nine power plants, replacing small units with large ones, backward capacity elimination, and regional restrictions. Specifically, 131 heavily polluting enterprises will be relocated from urban areas to more remote areas. (2) Implement more stringent emission standards to control the most significant categories of stationary sources of atmospheric pollutants. Among them, emission standards for power plant boilers are in line with the advanced international levels (SO_2 concentration $<=$ 50 mg m^{-3}; NO_x concentration $<=$ 100 mg m^{-3}; dust $<=$ 20 mg m^{-3}). (3) Efforts will also be made to drive forward the emission standards for mobile sources. National emission standard IV is currently effective for light gasoline vehicles. Requirements for heavy vehicles, motorcycles and non-road mobile machinery will be enhanced. Clean fuels and clean energy vehicles will be promoted. (4) Enhance the VOC emission control based on fuel vapor recovery, coating emission control, solvent usage requirements including replacement in some cases, and petrol industry upgrades. (5) Ship emission control and clean

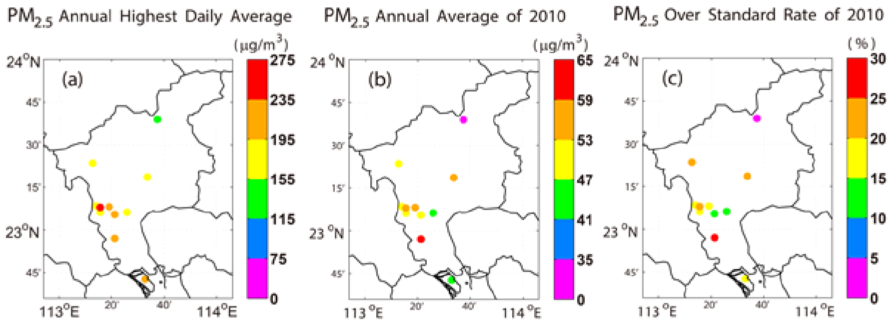

Fig. 5. $PM_{2.5}$ concentration ($\mu g\,m^{-3}$) at each of the 11 individual sites in Guangzhou region in 2010 of **(a)** the annual highest daily average, **(b)** the annual average and **(c)** over-standard rate.

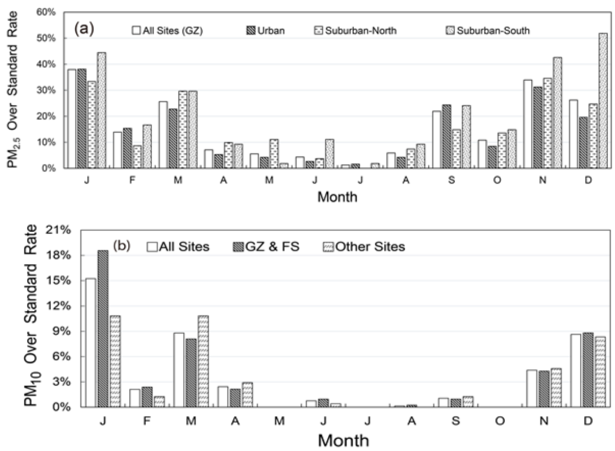

Fig. 6. Percentage of $PM_{2.5}$ or PM_{10} non-attainment days per month in 2010: **(a)** $PM_{2.5}$ in Guangzhou and **(b)** PM_{10} in PRD.

fuel processes. (6) Dust control. (7) Area source control, including emission reduction requirements for cooking, straw open burning, etc. (8) Actively explore the joint prevention and control mechanisms for regional atmospheric pollution with agencies outside of the local jurisdiction.

Based on those emission control plans, an estimate can be made of the changes in emission rates as well as source activity levels. The emission factor forecasting is relatively simple, primarily based on the strictest emission standards and best available technology, e.g., Euro 5 standards for vehicles, low NO_x combustion technology for new power plants, coal replacement with natural gas, high emission industry phase-out, clean energy vehicle replacement and similar control actions. The activity data forecasting can be summarized into the following categories: (1) based on historical data and development plans committed by local and regional authorities as mentioned above. This category includes power plants, industry and vehicle population. Total energy consumption would be increased by 102 %. The generating capacity will reach 68.7 billion kwh in 2025, 1.70 times higher than 2010. The industrial sector will increase to 1.03–2.30 times the 2010 level depending on the specific sector. In 2025, the vehicle population would be 5.97 million, which is 2.82 times the vehicle population in 2010. (2) Based on specific sector development plans created for the region. For example, the activity level of vessels, airports, railway, service stations, road construction and docks are generated based on comprehensive transportation system planning in Guangzhou. The number of construction sites is based on land use planning, which would be reduced by 19 %. Port cargo and container throughput would increase by 69 %. (3) Based on GDP, population, farmland area and other macro economy indicators. As forecasted, population would increase by 63 % from 2010 to 2025. In this category, most of the public use sources are covered, e.g., consumer products (solvent) usage. The agriculture vehicles are forecasted based on the area of farmland, which would be almost constant since 2010. Combined with our base year emission inventory, the emission reduction potential for both new sources and present sources were estimated using a bottom-up approach.

Figure 7 provides total estimated emission amounts from each category in 2010 and 2025. Both primary $PM_{2.5}$ emissions and other precursors' emissions would be reduced. SO_2 emissions would be reduced from 87 thousand tons in 2010 to 17 thousand tons in 2025. The other pollutants would be reduced as well, but not as aggressively as SO_2. The emission amount of NO_x, PM_{10}, $PM_{2.5}$ and VOCs in 2025 would be controlled to 119, 61, 26 and 163 thousand tons, reduced by 51.9 %, 55.9 %, 61.8 % and 41.3 % compared to 2010. Taking primary $PM_{2.5}$ emission as an example, the primary $PM_{2.5}$ emission amount would be reduced to 38 % of the 2010 level. Industrial emission control technology and clean energy would reduce emissions by 16.7 thousand tons of $PM_{2.5}$, followed by 9.1 thousand tons of reduction from power plants, and 8.8 thousand tons of reduction from transportation.

Sector-based reduction percentages provide an overview of the control strategy in each sector in the PRD (Fig. 8). Power plants, industry and mobile sources are three major

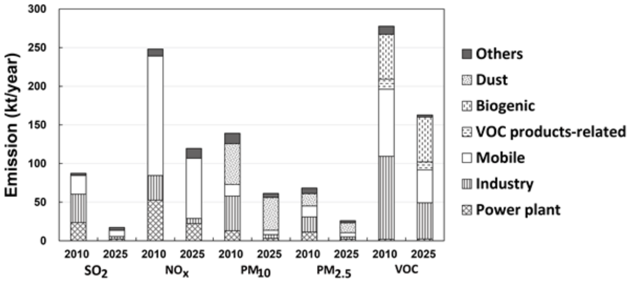

Fig. 7. Total emission amount from each category in Guangzhou in 2010 and 2025.

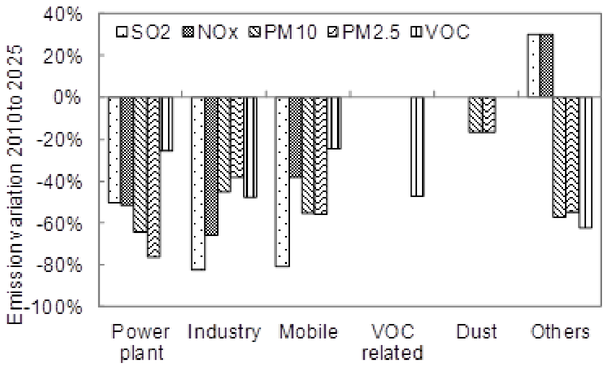

Fig. 8. Sector-based emission reduction percentage in PRD by 2025.

contributors for all pollutant reductions, which is similar within Guangzhou. There would be 68 %, 43 %, 38 %, 44 % and 29 % reduction of SO_2, NO_x, PM_{10}, $PM_{2.5}$ and VOCs from these three major sectors in PRD region. Product-related VOC controls would be important for VOC total amount control.

Figure 9 compares the contribution by each sector in 2010 and 2025. The major contributors of SO_2 emissions would become transportation (mainly from off-road transportation) and industry in 2025, as compared to power plants and industry in 2010, though the total amount would be very low. The percentage of particles from dust gets significant because of the decreasing amounts from other sectors. Mobile and biogenic contribution percentages to VOCs would increase, which highlights the need for further control in this sector.

It should be noted here that $PM_{2.5}$ results from a complex distribution of sources, including primary particulate matter directly emitted from pollution sources, and secondary particles formed from SO_2, NO_x and NH_3 in the atmosphere. For Guangzhou, a polluted southern city, it is more difficult to control the $PM_{2.5}$ pollution than the PM_{10} pollution in light of the nonlinear characteristic of the impact of natural sources and the formation process of secondary particulate matter. As we estimated in previous investigation, the concentration reductions of $PM_{2.5}$ could only reach 10.2 % with

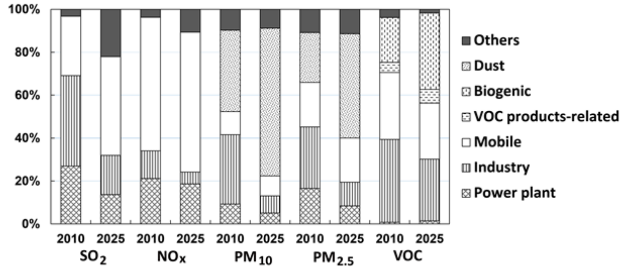

Fig. 9. Comparison of sector contribution in Guangzhou between 2010 and 2025.

emissions of NO_2 and primary $PM_{2.5}$ reduced by 14.8 % and 17.5 %, respectively, in Guangzhou (Liu et al., 2013). Thus, precursor emissions must be reduced by more than 35 % in each FYP period along with a compliance rate of about 80 % to achieve a decrease of 34 % in $PM_{2.5}$ ambient concentration (to achieve 35 $\mu g\,m^{-3}$) by 2025.

4 Air quality in the future

4.1 Air quality models and model evaluation

The MM5-STEM 2K3 modeling system was applied in this study. MM5-STEM 2K3 is an integrated model system which combines the Sulfur Transport and Deposition Model version 2K3 (STEM-2K3) and the Penn State/National Center for Atmospheric Research (NCAR) Fifth-Generation Mesoscale Meteorological Model version 3.7 (MM5v3.7). It includes the SAPRC99 gaseous mechanism (Carter, 2000) with photolysis rates calculated using the online TUV model (Madronich and Flocke, 1999). It was used in the Transport and Chemical Evolution over the Pacific (TRACE-P) experiment (Tang et al., 2003; Carmichael et al., 2003) and performed well compared with observed data in the PRD region (X. Wang et al., 2005, 2013; Liu et al., 2013). MM5 was run to produce the meteorological fields to drive the STEM-2K3. The performance of MM5 has been evaluated both for Guangzhou (Chen et al., 2010; Liu et al., 2013) and the other regions in previous studies (Streets et al., 2007). STEM was evaluated with six statistical metrics, i.e., average for observation (OBS) and simulation (SIM), absolute bias (ME), bias, root-mean-square error (RMSE), and the index of agreement (IOA), as calculated below, where S_i stands for the simulation and O_i stands for the observation.

$$\mathrm{OBS} = \frac{1}{n}\sum_{i=1}^{n} O_i \tag{1}$$

$$\mathrm{SIM} = \frac{1}{n}\sum_{i=1}^{n} S_i \tag{2}$$

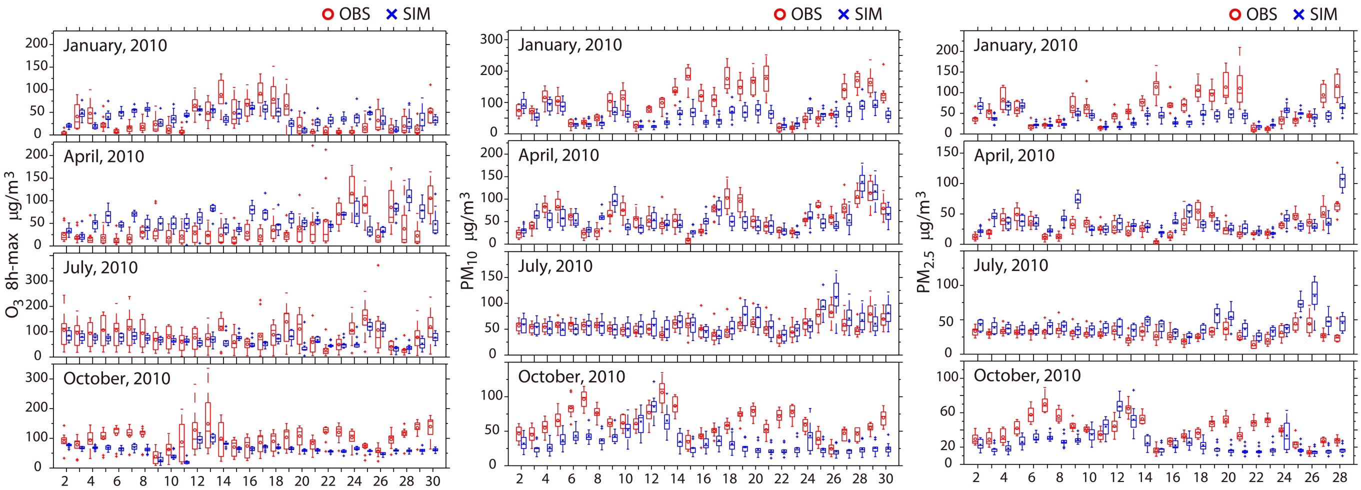

Fig. 10. Comparison between observed and simulated concentrations of air pollutants (daily maximum 8 h concentration of O_3, PM_{10} and $PM_{2.5}$) in January, April, July and October 2010. On each box, the central mark is the median, the edges of the box are the 25th (q1) and 75th (q3) percentiles, the whiskers extend to the most extreme data points not considered outliers, and points are drawn as outliers (symbol "+") if they are larger than q_3+1.5 (q_3–q_1) or smaller than q_1–1.5 (q_3–q_1). The open cycles and Xs are the observed and simulated averages, respectively.

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n} |S_i - O_i| \quad (3)$$

$$\mathrm{Bias} = \frac{1}{n}\sum_{i=1}^{n} (S_i - O_i) \quad (4)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (S_i - O_i)^2} \quad (5)$$

$$\mathrm{IOA} = 1 - \left[\frac{n \cdot RMSE^2}{\sum_{i=1}^{n} (|S_i| + |O_i|)^2}\right] \quad (6)$$

Two nested domains were applied for MM5, which cover the PRD region with a center located at 23 055° N and 113 402° E. The meteorology for January, April, July and October in 2010 was applied to drive the air quality model for the 2010 base case and 2025 scenarios. In this study, January, April, July and October were chosen as the representative month for each season (winter, spring, summer and fall, respectively); these were also used earlier by Liu et al. (2010) to save computing time. The ratios between PM_{10} observation and simulation for January, April, July and October are 1.7, 1.1, 0.9 and 1.7, respectively. In order to reflect the other months' simulation, we assumed that the ratio is invariant for the other two months in the same season. Thus, the simulation could be expanded to all months in 2010 by multiplying monthly observed data with the ratio of each season, calculated by the representative month. The average of 12-month simulations using this method of PM_{10} is 50 μg m^{-3}, while the observed annual average is 68 μg m^{-3}. The error is 26 %, which is in the acceptable range for this type of modeling (X. Wang et al., 2013; Liu et al., 2013). The target of model use in this study is to provide the annual concentration because the first step in air quality improvement is based on annual concentration attainment. Thus, the evaluation of compliance for $PM_{2.5}$ and PM_{10} with the annual standards was performed. Results of the statistical evaluation of daily maximum 8 h average O_3 (O_3 8 h-max), daily PM_{10} concentration and daily $PM_{2.5}$ concentration over 10 sites located in Guangzhou are listed in Table 1 and Table 2. Figure 10 compares the observed and simulated data for the 10 sites in January, April, July and October 2010. The IOA of the 3 pollutants is 0.60–0.95 (O_3 8 h-max), 0.76–0.99 (PM_{10}), and 0.69–0.99 ($PM_{2.5}$). During April and July, for PM_{10} and $PM_{2.5}$, the IOA ranges from 0.91 to 0.99 and from 0.86 to 0.99, showing a high agreement between simulation and observation. The results show that STEM-2K3 well simulated O_3, PM_{10} and $PM_{2.5}$ in April and July 2010 but slightly underestimated them in January and October 2010, especially during 19–23 October.

4.2 Air quality improvements

Analysis of air quality from MM5-STEM results suggests that the long-term control measures would achieve the $PM_{2.5}$ goal successfully by 2025 (Fig. 11). The annual average

Table 1. Statistical evaluation of pollutant simulation in January and April 2010 ($\mu g\,m^{-3}$).

Period	Site	O_3 8 h-max						PM_{10}						$PM_{2.5}$					
		OBS	SIM	ME	Bias	RMSE	IOA	OBS	SIM	ME	Bias	RMSE	IOA	OBS	SIM	ME	Bias	RMSE	IOA
Jan	1	20	32	21	12	24	0.83	109	79	49	−30	62	0.91	62	53	25	−9	29	0.94
	2	23	24	19	1	21	0.81	108	88	38	−20	46	0.95	74	54	31	−20	41	0.91
	3	21	32	20	11	23	0.85	114	68	55	−46	72	0.87	98	45	58	−53	79	0.76
	4	23	38	24	15	27	0.85	101	61	49	−40	64	0.87	96	42	57	−54	74	0.77
	5	30	42	29	11	32	0.85	115	56	59	−59	77	0.83	–	–	–	–	–	–
	6	20	36	21	15	25	0.84	68	56	32	−12	37	0.93	65	38	37	−27	53	0.80
	7	41	40	26	−1	32	0.88	119	54	67	−66	83	0.81	69	38	33	−31	43	0.86
	8	36	36	25	0	31	0.87	105	49	57	−55	70	0.82	107	35	72	−72	87	0.68
	9	52	46	34	−6	41	0.86	88	46	49	−42	60	0.84	76	34	47	−43	58	0.78
	10	63	61	34	−2	40	0.91	78	34	48	−45	60	0.76	67	27	43	−41	55	0.72
Apr	1	36	49	36	14	45	0.77	60	70	26	10	29	0.95	34	44	18	10	23	0.92
	2	38	37	24	−1	30	0.85	64	80	24	15	29	0.96	36	47	18	11	23	0.93
	3	14	46	35	33	41	0.60	60	64	24	5	30	0.95	40	42	18	2	23	0.94
	4	21	57	45	35	50	0.64	67	54	25	−13	31	0.94	43	36	20	−7	25	0.92
	5	26	55	40	29	47	0.73	72	55	24	−17	34	0.94	–	–	–	–	–	–
	6	24	61	46	37	52	0.68	47	47	19	0	24	0.95	32	31	17	0	21	0.91
	7	46	55	37	9	47	0.82	75	47	34	−28	41	0.91	41	32	18	−9	22	0.92
	8	59	62	46	3	60	0.81	52	43	19	−10	23	0.95	45	29	21	−16	28	0.88
	9	55	67	39	11	43	0.90	48	46	19	−2	25	0.95	32	33	14	1	19	0.94
	10	69	71	25	2	32	0.95	49	38	22	−11	27	0.92	50	27	26	−24	34	0.86

Sites name from 1 to 10: Guangya, 5School, Jiancezhan, Tianhu, Luhu, Guangshang, 86School, Panyu, Huadu, Jiulong. There is no $PM_{2.5}$ observed data in Luhu site.

Table 2. Statistical evaluation of pollutant simulation in July and October 2010 ($\mu g\,m^{-3}$)

Period	Site	O_3 8 h-max						PM_{10}						$PM_{2.5}$					
		OBS	SIM	ME	Bias	RMSE	IOA	OBS	SIM	ME	Bias	RMSE	IOA	OBS	SIM	ME	Bias	RMSE	IOA
Jul	1	94	61	38	−33	47	0.92	54	70	19	16	24	0.96	34	47	14	13	19	0.95
	2	15	49	34	34	37	0.68	68	86	19	18	25	0.97	34	52	19	18	25	0.92
	3	58	57	33	−1	46	0.86	63	76	15	13	19	0.98	44	49	7	6	9	0.99
	4	99	63	46	−36	77	0.82	53	65	13	12	19	0.98	48	43	13	−5	17	0.97
	5	89	64	45	−25	54	0.90	73	63	22	−10	26	0.97	–	–	–	–	–	–
	6	38	76	48	38	54	0.81	52	48	8	−4	11	0.99	40	35	8	−6	11	0.98
	7	131	64	67	−67	76	0.86	59	49	12	−9	16	0.98	31	36	7	6	11	0.98
	8	92	75	30	−17	41	0.95	45	40	8	−5	12	0.98	43	30	15	−13	16	0.95
	9	125	85	54	−40	67	0.91	47	54	11	7	14	0.98	40	45	10	5	14	0.98
	10	116	85	45	−31	57	0.93	46	47	8	0	10	0.99	36	35	8	0	9	0.99
Oct	1	79	61	25	−17	35	0.94	70	47	26	−23	30	0.94	53	34	22	−19	27	0.91
	2	60	49	34	−12	46	0.85	69	55	19	−14	25	0.96	47	35	17	−12	21	0.94
	3	102	60	43	−42	46	0.92	61	36	28	−25	34	0.89	47	27	23	−20	27	0.88
	4	40	63	23	22	27	0.93	47	34	16	−13	20	0.95	47	25	22	−22	27	0.87
	5	125	67	58	−58	64	0.89	64	31	34	−34	38	0.85	–	–	–	–	–	–
	6	127	64	63	−63	80	0.85	54	36	20	−18	25	0.93	52	25	26	−26	31	0.86
	7	125	65	60	−60	72	0.87	73	30	43	−43	47	0.81	47	23	25	−24	30	0.84
	8	89	58	37	−30	47	0.91	61	39	25	−22	29	0.92	58	29	30	−29	35	0.86
	9	110	65	49	−45	56	0.90	69	26	44	−43	49	0.75	60	20	41	−40	45	0.71
	10	118	71	46	−46	54	0.92	54	20	35	−35	38	0.76	54	17	38	−37	42	0.69

Sites name from 1 to 10: Guangya, 5School, Jiancezhan, Tianhu, Luhu, Guangshang, 86School, Panyu, Huadu, Jiulong. There is no $PM_{2.5}$ observed data in Luhu site.

concentration would be reduced from 53 $\mu g\,m^{-3}$ in 2010 to 27 $\mu g\,m^{-3}$ in 2025.

The PM_{10} annual average concentration is applied to understand the air quality trend since 2000 (Fig. 12). Data before 2012 are observed while the others are estimated. The new NAAQS and CIP would be a milestone for air quality improvement in Guangzhou. The PM_{10} annual average concentration increased from 2000 to 2003 and decreased from 2005 to 2008. After 2008, the concentrations are stable until 2012. With the implementation of the CIP beginning in 2013, the PM_{10} concentration should start decreasing again. The annual average concentration of PM_{10} could be lower than 40 $\mu g\,m^{-3}$ in 2025.

In this study, emissions outside the PRD region are set as constant for model input from 2010 to 2025. Most likely, other regions will take control measures similar to the PRD

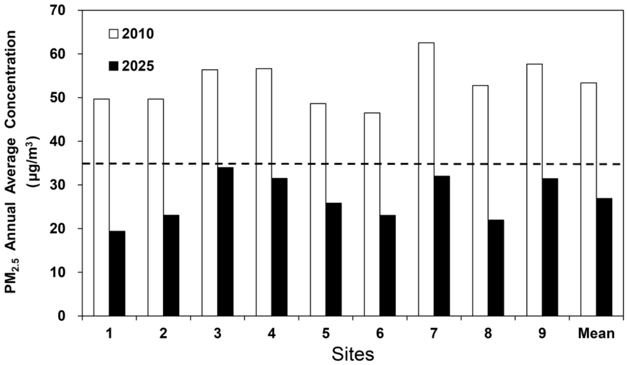

Fig. 11. $PM_{2.5}$ annual average concentration ($\mu g\, m^{-3}$) in Guangzhou, 2010 and 2025. (Sites name from 1 to 9: Guangya, 5School, Jiancezhan, Tianhu, Guangshang, 86School, Panyu, Huadu, Jiulong).

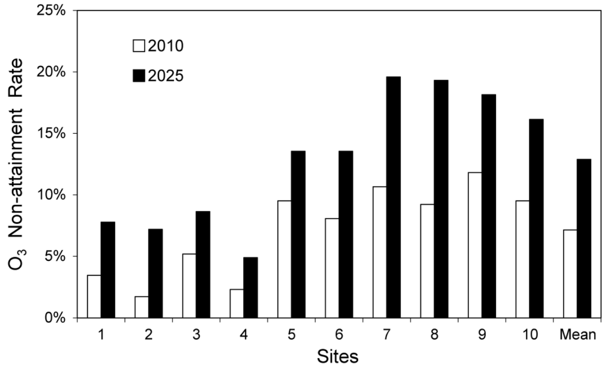

Fig. 13. Ozone non-attainment rate (by maximum 8 h average concentration) in Guangzhou, 2010 and 2025. (Sites name from 1 to 10: Guangya, 5School, Jiancezhan, Tianhu, Luhu, Guangshang, 86School, Panyu, Huadu, Jiulong).

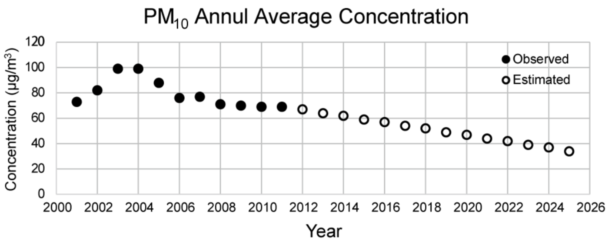

Fig. 12. Long-term PM_{10} annual average concentration ($\mu g\, m^{-3}$) trend in Guangzhou, 2000–2025.

region, so long-range transport from outside into the PRD will likely decrease in future. Thus the current projection of the air quality is a conservative one, that is, actual air quality will be better if a decrease of outside transport is considered.

4.3 Remaining problems

Under current strategy, the O_3 control will be problematic. The average non-attainment rate of maximum 8 h average concentrations would be increased from 7.1 % in 2010 to 12.9 % in 2025 (Fig. 13). In some monitoring sites, the non-attainment rate in 2025 would go as high as 19.6 %, similar to the worst month in 2010. Based on this estimation, the average O_3 peak concentration in 2025 would reach 318 $\mu g\, m^{-3}$ in Guangzhou. In this study, the meteorology condition is kept the same as in 2010, while the PRD regional emission is projected based on the regional plan. The control measures in other regions of China have not been considered in this study. Thus, the ozone violation is mainly relevant to the local emission changes, which means the increase in the VOCs / NO_x ratio and the changes of reactive species in VOCs. On one hand, the VOCs / NO_x emission ratio would increase by 22 % and 25 % in Guangzhou and in PRD, respectively, from 2010 to 2025. On the other hand, biogenic VOCs (BVOCs) are especially important because they are usually highly reactive, e.g., isoprene and monoterpenes. Recently, a new study reported that Guangzhou is a place where surface ozone is very sensitive to BVOC emissions in both autumn and summer. The results show BVOC emissions increase the daytime ozone peak by 3 ppb on average, and the max hourly impact of BVOC emissions on the daytime ozone peak is 24.8 ppb (Situ, 2013). In our forecast, biogenic emissions would become the biggest sources of VOC emissions in 2025, which contribute 36 % in total. The ratio of BVOCs to NO_x would be increased from 23 % to 48 % in 2025. A high ratio of reactivity-weighted VOCs to NO_x contributes significantly to boundary layer ozone formation.

As mentioned in the Introduction, the current ozone pollution is already serious in the PRD region. Unfortunately, such $PM_{2.5}$-based emission control scenarios would enhance the ozone pollution problems. Ozone pollution will remain the primary and the most difficult atmospheric environmental problem facing Guangzhou for quite a long period of time. In addition, increased ozone concentration might lead to the increased oxidability of atmosphere, which will possibly enhance the ozone–$PM_{2.5}$ oxidation mechanism and finally increase the formation of secondary aerosols. In our investigation, the secondary aerosols' formation is included in current modeling for annual average concentration. In the future, with advanced air quality models including O_3–$PM_{2.5}$ complex oxidation mechanism, the day-by-day $PM_{2.5}$ concentration and secondary aerosols could be better understood. This would be an important research topic to fully understand the air quality forecast and evaluation in the future study.

In 2025, the amount of NO_x and total VOC emissions in the PRD region would have declined by 43.4 % and 29 %, respectively, from 2010, which would result in an increase in the VOCs / NO_x ratio from 1.2 to 1.5. In such emission control, the monthly average of maximum 8 h average concentrations of O_3 in July would be increased from 81 $\mu g\, m^{-3}$ to 101 $\mu g\, m^{-3}$, and its non-attainment rate would be double

Table 3. Comparison of VOCs and NO_x emission control in California and Guangzhou.

Emission	California	Guangzhou
VOC emission / NO_x emission	1.3 (1985)	1.1 (2010)
VOC emission / NO_x emission	0.7 (2005)	1.4 (2025)
VOC reduction amount / NO_x reduction amount	3 : 1	0.9 : 1

that of 2010. In order to figure out whether the enhance ozone production is the result of an increase in the VOCs / NO_x ratio, we made another two emission sensitivity experiments, 2025 test 1 and 2025 test 2 (see Table 4). Compared to January, April and October, there are the most significant changes in July from 2010 to 2025. Thus, only July was chosen to be the simulated period for 2025 test 1 and 2025 test 2 to save computing time.

Compared to scenario 2025, 2025 test 1 has a much stronger control in VOC emission, which reduces the VOCs / NO_x ratio to 0.7 from 1.5, while NO_x emission stays at the same level. In this test (see Table 4), the monthly average of maximum 8 h average concentrations of O_3 in July would be decreased from 101 $\mu g\,m^{-3}$ to 87 $\mu g\,m^{-3}$, and its non-attainment rate would be decreased from 20 % to 11.7 %. It shows a similar result to some previous studies focused on the PRD region (Shao et al., 2009; Wang et al., 2011). But it is still a little worse than 2010, which might be resulted from a stronger control in NO_x emission. Therefore, in 2025 test 2, we try to make less reduction in NO_x emission while the VOCs / NO_x ratio still equals 0.7. The amount of NO_x and VOC emissions declined by 20 % and 52.7 %, respectively, from 2010, which makes the VOCs / NO_x ratio decrease from 1.2 to 0.7. In such emission control, the monthly average of maximum 8 h average concentrations of O_3 in July would be decreased from 81 $\mu g\,m^{-3}$ in 2010 to 79 $\mu g\,m^{-3}$, and its non-attainment rate would be decreased from 10 % in 2010 to 7.9 % in 2025.

According to these experiments, we proved that Guangzhou is in a VOC-limited region (Shao et al., 2009; Wang et al., 2011) and the large increase in VOCs / NO_x would lead to increase in ozone in the Guangzhou urban area. The ozone violation rate could have a decrease in 2025 only if the ratio of VOCs and NO_x emission in the PRD region could be controlled to an appropriate range and appropriate absolute amount.

In accordance with the previous analysis, Guangzhou needs to make improvements in regulations, management mechanism, capacity building, and control measures in order to fully achieve air quality standards. The challenges to achieve ozone goals include aspects both of science and policy. Generally, evidence-based multi-pollutant and multi-control policies are necessary. A scientific research focus on ozone–PM co-improvement is important for future. The next section will discuss the implication of O_3 control from international experience. Long-term international ozone control experiences also warn us as to the difficulties in O_3 attainment in a VOC-limited area.

5 Implication of ozone control from southern California practices

5.1 Similar gaps and schedule

Guangzhou and California share a lot of similarity with respect to air pollution causes, its characteristics, and its control. Both of them are important economic hubs and suffer high ozone concentration. The gross domestic product (GDP) in Guangdong was about USD 800 billion in 2010, contributing 10.9 % of the national total and ranking first in China. According to the 2010 statistics, the GDP of California reached USD 1936.4 billion, accounting for 13.34 % of the United States GDP, which is the highest in the nation. In the past decade, the growth of the Guangdong economy and vehicle use is very similar to the urban sprawl in California after World War II. The annual GDP grew at a rate of over 10 %, accompanied by rapid growth of vehicle population (13.5 % annually) and related fuel consumption.

Along with these increases is the emergence of severe air pollution. For both statistics, southern California had the greatest number of violations of the then-new 8 h standard in the US from 1980 to 1998. However, with continuous efforts, great air quality improvement has been achieved in California. However, the PRD is facing even more serious challenges, due much to the late start of air quality management, the continuously soaring economy, and numerous manufacturing facilities. The following section provides three implications from California based on historical data analysis.

5.2 Implication 1: scientific ratio of VOCs / NO_x reduction

During 1988 through 2007 in California, statewide maximum 8 h ozone values decreased 47 percent, and maximum 8 h carbon monoxide values dropped 73 percent (Fig. 14). These air quality improvements occurred at the same time (1985–2005) the State's population increased 40 percent and the average daily VMT increased 77 percent. Emissions of NO_x and reactive organic gases (ROGs) in California were about 4744 and 5990 tons day^{-1} in 1985, and the ROG / NO_x ratio was about 1.3. In 2005, the amount of NO_x and ROG emissions were reduced to 3513 and 2455 tons day^{-1} (ROG / NO_x ratio 0.7). On a statewide basis, NO_x emissions declined by 26 % (1231 tons day^{-1}) between 1985 and 2005. Emissions of ROG in California decreased by 59 % (3535 tons day^{-1}) from 1985, which is about double the percentages of NO_x reduction. In addition, before this big step, emissions of NO_x in California remained relatively stable between 1975 and 1985, only decreasing by 3 %, while the emissions of ROG decreased 15 % between 1975 and 1985.

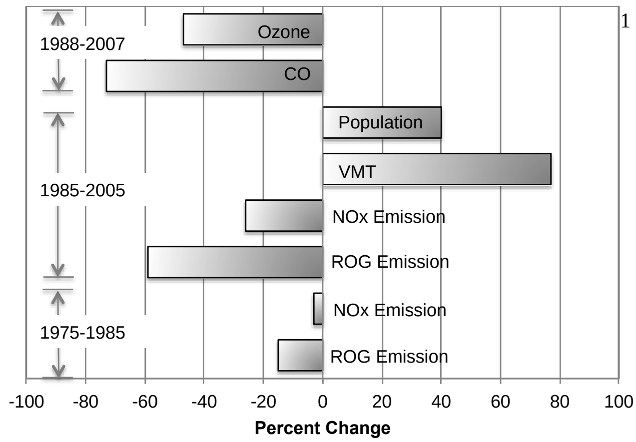

Fig. 14. Percent change in air quality, growth and emissions in California (the California Air Resources Board's (ARB's) Emission Inventory Branch (EIB) uses the term reactive organic gases (ROG) instead of VOCs in their analysis).

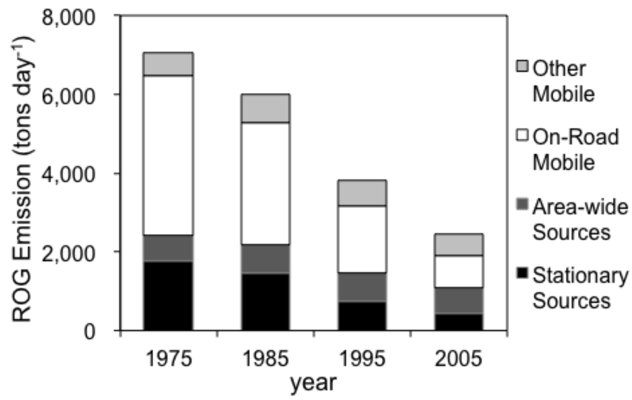

Fig. 15. ROG emissions by sectors in California.

Emissions of NO_x and VOCs in Guangzhou were about 680 and 761 tons day^{-1} in 2010, as shown in Fig. 7. Table 3 summarizes the controls in California and Guangzhou. In Guangzhou, the VOCs / NO_x ratio was about 1.1 in 2010, similar to California in 1985. The difference is that in California the VOCs / NO_x ratio was successfully reduced to 0.7 in twenty years, while this ratio is forecasted to increase to 1.4 in Guangzhou in fifteen years from 2010. Both this study and the California VOC emission data provide only total VOC or ROG emission amounts without detailed species and ozone formation potential information. More scientific studies in the PRD region are needed to support the evaluation of control strategies and ozone effects. These studies must consider the difference in VOC composition, OH concentration levels, and individual species reactivity levels. Nevertheless, Guangzhou needs very strong control of VOCs to reduce its ozone.

5.3 Implication 2: VOC control sectors

The sector distribution of VOC emissions in California was further investigated to find out the reduction potential. Figure 15 is a statewide ROG emission trend referenced from the ARB Almanac 2009 (The California Almanac of Emissions and Air Quality – 2009 Edition; http://www.arb.ca.gov/aqd/almanac/almanac09/almanac09.htm). ROG emissions in California were decreasing, largely as a result of the state's on-road motor vehicle emission control program. This includes the control of evaporative emissions and tailpipe emissions. The use of improved evaporative emission control systems (Onboard Refueling Vapor Recovery, ORVR) has reduced refueling and diurnal emissions effectively. Computerized fuel injection, engine management systems are needed to meet increasingly stringent California emission standards along with cleaner gasoline. The Smog Check program is also contributing to the needed ROG reduction. ROG emission reduction from other mobile sources is due to more stringent emission standards. Substantial reductions have also been obtained for area-wide sources through the vapor recovery program for service stations, bulk plants, and other fuel distribution operations. There are also on-going programs to reduce overall solvent ROG emissions from coatings, consumer products, cleaning and degreasing solvents, and other substances used within California.

The Guangzhou government has taken some of the needed measures to reduce its VOC emissions. The next step should be, although it would be not easy, to enhance the following control activities: inspection of vapor recovery program for service stations, vehicle evaporative emission control systems, bulk plants, and other fuel distribution operations, solvent evaporative emissions from coating and consumer products, cleaner gasoline and similar sources. Those measures above are not only technical issues, but also management issues. To get full advantage of the VOC control measures, frequent inspection and maintenance are very important, which means more labor costs and management work.

5.4 Implication 3: ozone transport

Since 1989, the California government has evaluated the impacts of the transport of ozone and ozone precursor emissions from upwind areas to the ozone concentrations in downwind areas. These analyses demonstrate that the air basin boundaries are not true boundaries of air masses. All urban areas are upwind contributors to their downwind neighbors with the possible exception of San Diego. Areas impacted by overwhelming transport, although designated non-attainment, are not able to achieve the air quality goals because local control strategies in these areas would not be adequate by themselves to meet air quality improvement needs. However, these areas

Table 4. Comparison of VOC and NO_x emission in PRD and its effect on O_3 during July in Guangzhou between different schemes.

	NOx ($kt\,yr^{-1}$)	Total VOCs VOCs ($kt\,yr^{-1}$)	BVOCs ($kt\,yr^{-1}$)	Anthro-pogenic ($kt\,yr^{-1}$)	VOCs / NO_x	Reduction VOCs / NO_x	Monthly O_3-8 h ($\mu g\,m^{-3}$)	Non-attainment rate
2010	1034	1224	270	954	1.2	–	81	10.0 %
2025	586	869	270	599	1.5	0.8	101	20.0 %
2025 – test 1	586	410	270	140	0.7	2.8	87	11.7 %
2025 – test 2	827	579	270	309	0.7	3.1	79	7.9 %

are subject to many local control strategies, such as cleaner fuels and low-emission vehicles (Keating and Farrell, 1999).

On regional transport of ozone, previous observation (T. Wang et al., 2009) and modeling (Li et al., 2012) have already shown significant impact of long-range transport on ozone in the HK/PRD region, especially the impact from continent-influenced air-mass groups from upwind areas. In the future, regional ozone air quality plans in Guangzhou must take into account the shared responsibility between upwind and downwind areas where transport can at times be significant.

6 Concluding remarks

Our evaluation of Guangzhou's starting position and future air quality trends suggests that several straightforward, feasible and practical measures can be taken to dramatically improve $PM_{2.5}$ concentration and public health protection in the near term. In addition, by shifting from the pollutant-by-pollutant mode to multi-pollutant control, China will immediately align its public policy decisions and investments in a rational way. Streamlining regulatory authority and enforcement will ensure effective execution of air quality management practices from the national government all the way down to the factory floor. Regional cooperation efforts would help the evolution of industrial growth and emission control and provide an evidence-based air quality framework for regional air quality management. Air quality problems can be at least partly solved in the coming 15 yr. The current projection of the air quality is a conservative one without consideration of the decrease of outside transport. Ozone will likely still be a compliance issue with the new NAAQS and it might lead to the increased oxidability of atmosphere, which will possibly enhance the formation of secondary aerosols. The next step may need to further investigate $PM_{2.5}$ compliance under increased atmospheric oxidation, and O_3–$PM_{2.5}$ co-improvement Guangzhou needs very strong control of VOCs to reduce its ozone. The key solution to the O_3 issue will be VOC emission reductions from multiple sectors. The VOCs / NO_x reduction ratio should be increased (in California, it is about 3 : 1), instead of the current plan of 0.9 : 1. The evaporative emission control from vehicle non-tailpipe emission and solvent usage should be enhanced and regional ozone transport must be taken into account.

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References

Biswas, P., Wang, W., and An, W.: The energy-environment nexus, aerosol science and technology enabling solutions, Front. Environ. Sci. Engin., 5, 299–312, 2011.

Carmichael, G. R., Tang, Y., Kurata, G., Uno, I., Streets, D. G., Thongboonchoo, N., Woo, J. H., Guttikunda, S., White, A., Wang, T., Blake, D. R., Atlas, E., Fried, A., Potter, B., Avery, M. A., Thorton, D., and Clarke, A. D.: Evaluating regional emission estimates using the TRACE-P observations, J. Geophys. Res., 108, 8810, doi:10.1029/2002JD003116, 2003.

Carter, W.: Documentation of the SAPRC-99 chemical mechanism for VOC reactivity assessment, c. n., Final Report to California Air Resources Board Riverside, University of California at Riverside, 2000.

Chan, C. K. and Yao X.: Air pollution in mega cities in China, Atmos. Environ., 42, 1–42, 2008.

Chen, H., Wang, Z., Wu, Q., and Wang, W.: Source analysis of Guangzhou air pollutants by numerical simulation in the Asian Games Period, Acta Sci. Circumst., 30, 2145–2153, 2010 (in Chinese).

Donkelaar, A. V., Martin, R. V., Brauer, M., Kahn, R., Levy, R., Verduzco, C., and Villeneuve P. J.: Global Estimates of Ambient Fine Particulate Matter Concentrations from Satellite-Based Aerosol Optical Depth, Development and Application, Environ. Health Persp., 118, 847–855, 2010.

Gao, H., Chen, J., Wang, B., Tan, S.-C., Lee, C. M., Yao, X., Yan, H., and Shi, J.: A study of air pollution of city clusters, Atmos. Environ., 45, 3069–3077, 2011.

Geng, F., Zhang, Q., Tie, X., Huang, M., Ma, X., Deng, Z., Yu, Q., Quan, J., and Zhao C.: Aircraft measurements of O_3, NO_x, CO, VOCs, and SO_2 in the Yangtze River Delta region, Atmos. Environ., 43, 584–593, 2009.

Geng, Y. and Sarkis, J.: Achieving National Emission Reduction Targe- China's New Challenge and Opportunity, Environ. Sci. Technol., 46, 107–108, 2012.

Hao, J. and Walsh, M.: Regional Air Quality Integrated Control System Research, Beijing, CCICED Special Policy Study, 2012.

Karatzas, K., Dioudi, E., and Moussiopoulos, N.: Identification of major components for integrated urban air quality management and information systems via user requirements prioritisation, Environ. Model. Soft., 18, 173–178, 2003.

Keating, T. J. and Farrell, A.: Transboundary Environmental Assessment, Lessons from the Ozone Transport Assessment Group, National Center for Environmental Decision-making Research, 1999.

Li, Y., Lau, A. K. H., Fung, J. C. H., Zheng, J. Y., Zhong, L. J., and Louie, P. K. K.: Ozone source apportionment (OSAT) to differentiate local regional and super-regional source contributions in the Pearl River Delta region, China, J. Geophys. Res., 117, D15305, doi:10.1029/2011JD017340, 2012.

Liu, H., Wang, X., Zhang, J., He, K., Wu, Y., and Xu, J.: Emission controls and changes in air quality in Guangzhou during the Asian Games, Atmos. Environ., 76, 81–93, 2013.

Liu, X., Zhang, Y., Xing, J., Zhang, Q., Wang, K., Streets, D. G., Jang, C., Wang, W., and Hao, J.: Understanding of regional air pollution over China using CMAQ, Pt. II, Process analysis and sensitivity of ozone and particulate matter to precursor emissions, Atmos. Environ., 44, 3719–3727, 2010.

Lu, Q., Zheng, J., Ye, S., Shen, X., Yuan, Z., and Yin, S.: Emission trends and source characteristics of SO_2, NO_x, PM_{10} and VOCs in the Pearl River Delta region from 2000 to 2009, Atmos. Environ., 76, 11–20, 2013.

Madronich, S. and Flocke, S.: Handbook of Environmental Chemistry, Heidelberg, Springer, 1999.

Peng, G. L., Wang, X. M., Wu, Z. Y., Wang, Z. M., Yang, L. L., Zhong, L. J., and Chen, D. H.: Characteristics of particulate matter pollution in the Pearl River Delta region, China, an observational-based analysis of two monitoring sites, J. Environ. Monitor., 13, 1927–1934, 2011.

Ponche, J.-L. and Vinuesa, J.-F.: Emission scenarios for air quality management and applications at local and regional scales including the effects of the future European emission regulation (2015) for the upper Rhine valley, Atmos. Chem. Phys., 5, 999–1014, doi:10.5194/acp-5-999-2005, 2005.

Schreifels, J. J., Fu, Y., and Wilson, E. J.: Sulfur dioxide control in China: policy evolution during the 10th and 11th Five-year Plans and lessons for the future, Energ. Polic., 48, 779–789, 2012.

Shao, M., Zhang, Y., Zeng, L., Tang, X., Zhang, J., Zhong, L., and Wang, B.: Ground-level ozone in the Pearl River Delta and the roles of VOC and NO_x in its production, J. Environ. Manage., 90, 512–518, 2009.

Situ, S., Guenther, A., Wang, X., Jiang, X., Turnipseed, A., Wu, Z., Zhou, G., Bai, J., and Wang, X.: Impacts of seasonal and regional variability in biogenic VOC emissions on surface ozone in the Pearl River Delta region, China, Atmos. Chem. Phys. Discuss., 13, 6729–6777, doi:10.5194/acpd-13-6729-2013, 2013.

Streets, D. G., Fu, J. S., Jang, C. J., Hao, J., He, K., Tang, X., Zhang, Y., Wang, Z., Li, Z., Zhang, Q., Wang, L., Wang, B., and Yu, C.: Air quality during the 2008 Beijing Olympic Games, Atmos. Environ., 41, 480–492, 2007.

Tan, J., Duan, J., He, K., Ma, Y., Duan, F., Chen, Y., and Fu, J.: Chemical characteristics of $PM_{2.5}$ during a typical haze episode in Guangzhou, J. Environ. Sci., 21, 774–781, 2009.

Tang, Y. H., Carmichael, G. R., Woo, J. H., Thongboonchoo, N., Kurata, G., Uno, I., Streets, D. G., Blake, D. R., Weber, R. J., Talbot, R. W., Kondo, Y., and Singh, G. B.: The influences of biomass burning during TRACE-P experiment identified by the regional chemical transport model, J. Geophys. Res., 108, 8824, doi:10.1029/2002JD003110, 2003.

Tie, X., Geng, F., Peng, L., Gao, W., and Zhao, C.: Measurement and modeling of O_3 variability in Shanghai, China: Application of the WRF-Chem model, Atmos. Environ., 43, 4289–4302, 2009.

Verma, R. L., Sahu, L. K., Kondo, Y., Takegawa, N., Han, S., Jung, J. S., Kim, Y. J., Fan, S., Sugimoto, N., Shammaa, M. H., Zhang, Y. H., and Zhao, Y.: Temporal variations of black carbon in Guangzhou, China, in summer 2006, Atmos. Chem. Phys., 10, 6471–6485, doi:10.5194/acp-10-6471-2010, 2010.

Wang, T., Ding, A., Gao, J., and Wu, W. S.: Strong ozone production in urban plumes from Beijing, China, Geophys. Res. Lett., 33, L21806, doi:10.1029/2006GL027689, 2006.

Wang, T., Wei, X. L., Ding, A. J., Poon, C. N., Lam, K. S., Li, Y. S., Chan, L. Y., and Anson, M.: Increasing surface ozone concentrations in the background atmosphere of Southern China, 1994–2007, Atmos. Chem. Phys., 9, 6217–6227, doi:10.5194/acp-9-6217-2009, 2009.

Wang, T., Nie, W., Gao, J., Xue, L. K., Gao, X. M., Wang, X. F., Qiu, J., Poon, C. N., Meinardi, S., Blake, D., Wang, S. L., Ding, A. J., Chai, F. H., Zhang, Q. Z., and Wang, W. X.: Air quality during the 2008 Beijing Olympics: secondary pollutants and regional impact, Atmos. Chem. Phys., 10, 7603–7615, doi:10.5194/acp-10-7603-2010, 2010.

Wang, X., Carmichael, G., Chen, D., Tang, Y., and Wang, T.: Impacts of different emission sources on air quality during March 2001 in the Pearl River Delta (PRD) region, Atmos. Environ., 39, 5227–5241, 2005.

Wang, X., Zhang, Y., Hu, Y., Zhou, W., Zeng, L., Hu, M., Cohan, D. S., and Russell, A. G.: Decoupled direct sensitivity analysis of regional ozone pollution over the Pearl River Delta during the PRIDE-PRD2044 campaign, Atmos. Environ., 45, 4941–4949, 2011.

Wang, X., Liu, H., Pang, J., Carmichael, G., He, K., Zhong, L., Wu, Z., Zhang, J., and Peng, G.: Reductions in sulfur pollution in the Pearl River Delta region, China, Assessing the effectiveness of emission controls, Atmos. Environ., 76, 113–124, 2013.

Wang, Y., Hao, J., McElroy, M. B., Munger, J. W., Ma, H., Chen, D., and Nielsen, C. P.: Ozone air quality during the 2008 Beijing Olympics: effectiveness of emission restrictions, Atmos. Chem. Phys., 9, 5237–5251, doi:10.5194/acp-9-5237-2009, 2009.

Wang, Y., Zhang, Q. Q., He, K., Zhang, Q., and Chai, L.: Sulfate-nitrate-ammonium aerosols over China: response to 2000–2015 emission changes of sulfur dioxide, nitrogen oxides, and ammonia, Atmos. Chem. Phys., 13, 2635–2652, doi:10.5194/acp-13-2635-2013, 2013.

Xing, J., Wang, S. X., Chatani, S., Zhang, C. Y., Wei, W., Hao, J. M., Klimont, Z., Cofala, J., and Amann, M.: Projections of air pollutant emissions and its impacts on regional air quality in China in 2020, Atmos. Chem. Phys., 11, 3119–3136, doi:10.5194/acp-11-3119-2011, 2011.

Xue, W., Wang, J., Niu, H., Yang J., Han, B., Lei, Y., Chen, H., and Jiang, C.: Assessment of air quality improvement effect under the National Total Emission Control Program during the Twelfth National Five-Year Plan in China, Atmos. Environ., 68, 74–81, 2013.

Yan, X. and Crookes, R. J.: Reduction potentials of energy demand and GHG emissions in China's road transport sector, Energ. Poli., 37, 658–668, 2009.

Yuan, Y., Liu, S., Castro, R., and Pan, X.: $PM_{2.5}$ Monitoring and Mitigation in the Cities of China, Environ. Sci. Technol., 46, 3627–3628, 2012.

Zhao, Y., Zhang, J., and Nielsen, C. P.: The effects of recent control policies on trends in emissions of anthropogenic atmospheric pollutants and CO_2 in China, Atmos. Chem. Phys., 13, 487–508, doi:10.5194/acp-13-487-2013, 2013.

Zheng, J., Shao, M., Che, W., Zhang, L., Zhong, L., Zhang, Y., and Streets, D.: Speciated VOC Emission Inventory and Spatial Patterns of Ozone Formation Potential in the Pearl River Delta, China, Environ. Sci. Technol., 43, 8580–8586, 2009a.

Zheng, J., Zhang, L., Che, W., Zheng, Z., and Yin, S.: A highly resolved temporal and spatial air pollutant emission inventory for the Pearl River Delta, China and uncertainty assessment, Atmos. Environ., 43, 5112–5122, 2009b.

Zheng, J., Zhong, L., Wang, L., Louie, P., and Li, Z.: Ground-level ozone in the Pearl River Delta region, analysis of data from a recently established regional air quality monitoring network, Atmos. Environ., 44, 814–823, 2010.

Zhong L., Louie, P., Zheng, J., Wai, K. M., Ho, J., Yuan, Z., Lau, A., Yue, D., and Zhou, Y.: The Pearl River Delta regional air quality monitoring network – regional collaborative efforts on joint air quality management, Aerosol Air Qual. Res., accepted, doi:10.4209/aaqr.2012.10.0276, 2012.

Zhong, L., Louie, P. K. K., Zheng, J., Yuan, Z., Yue, D., Ho, J. W. K., and Lau, A. K. H.: Science-policy interplay, Air quality management in the Pearl River Delta region and Hong Kong, Atmos. Environ., 76, 3–10, 2013.