Atmos. Chem. Phys. Discuss., 13, 20923–20959, 2013
www.atmos-chem-phys-discuss.net/13/20923/2013/
doi:10.5194/acpd-13-20923-2013

Atmospheric Chemistry and Physics Discussions
Open Access

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

H. Liu[1], X. M. Wang[2], J. M. Pang[2], and K. B. He[1,3]

[1]State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, School of Environment, Tsinghua University, Beijing, China
[2]School of Environmental Science and Engineering, Sun Yat-Sen University, Guangzhou, China
[3]State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing, China

Received: 24 June 2013 – Accepted: 19 July 2013 – Published: 12 August 2013

Correspondence to: X. M. Wang (eeswxm@mail.sysu.edu.cn) and
K. B. He (hekb@tsinghua.edu.cn)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Improving the air quality in China is a long and arduous task. Although China has made very aggressive plan on pollutants control, the difficulties to achieve the new air quality goals are still significant. In north, $PM_{2.5}$ and PM_{10} are still far beyond the standards. In south, O_3 goal is much challenged. A lot of cities are making their city implementation plan (CIP) for new air quality goals. In this study, a southern city, Guangzhou, is selected to analyze the feasibility and difficulties on new air quality standard compliance, as well as the CIP evaluation. A comprehensive study of air quality status in Guangzhou and surrounding area is conducted based on 22 sites monitoring data of O_3, $PM_{2.5}$ and PM_{10}. The monthly non-attainment rates for O_3 vary in 7–25 % from May to November. The city average $PM_{2.5}$ concentration is 41 $\mu g\,m^{-3}$ in Guangzhou in 2010, which needs to be reduced by at least 15 % to achieve the target of 35 $\mu g\,m^{-3}$. The $PM_{2.5}$ high violate months are from November to March. Guangzhou CIP was then evaluated with $PM_{2.5}$ and O_3 placed in a core position. The emission amount of NO_x, PM_{10}, $PM_{2.5}$ and VOC in 2025 would be controlled to 600, 420, 200 and 860 thousand tons respectively. Analysis of air quality using the MM5-STEM model 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 20.8 $\mu g\,m^{-3}$ in 2025. The O_3 non-attainment rate would increase from 7.1 % in 2010 to 12.9 % in 2025 and become the most primary atmospheric environmental problem. Guangzhou needs very strong control on VOCs to reduce its ozone. The VOC / NO_x reduction ratio should reach at least 2 : 1 (in California, it is about 3 : 1), instead of the current plan of 0.7 : 1. The evaporative emissions control from vehicle non-tailpipe emission and solvent usage should be enhanced and regional ozone transport must be taken into account.

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 – 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 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 (Wang et al., 2013; Xing et al., 2011; Zhao et al., 2012; Yan and Crookes, 2009; Wang et al., 2010a, b; Schreifels et al., 2012; Xue et al., 2013; Geng and Sarkis, 2012). Targets of atmospheric pollutant emissions reduction are primarily based on emission reduction technologies and economic potential, rather than on the requirement of human health for air quality. Air quality assessment used to taking 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 health standard for $PM_{2.5}$ was setting at 35 µg 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 WHO air quality standards, has introduced a stricter limit for PM_{10} and NO_2 in the annual average, so that the PM_{10} and NO_2 standards are in line with the WHO Phase I 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. In accordance with the NAAQS, cities where the annual average concentration of SO_2, NO_2 and PM_{10} is higher than the standards number 18, 51 and 201 of the 333 cities respectively (Hao et al., 2012). 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. In north, PM_{10} concentrations are still far beyond the standards. In south, O_3 goal is very challenged (Geng et al., 2009; Tie et al., 2009; Liu et al., 2010; Gao et al., 2011; Wang et al., 2011; Zheng et al., 2009a, 2010). No large-scale applications of $PM_{2.5}$ monitoring had been attempted prior to the new NAAQS, and thus no enough data exist on the fate of concentration and variation all over China. 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).

Research needs to be developed to better understand the accessibility to attain the new NAAQS. Ministry of Environment Protection (MEP) in China has required each city preparing the City Implementation Plan (CIP) to achieve the new goals. However, as mentioned above, no large-scale $PM_{2.5}$ monitoring is one of the obstacles for making a CIP. Another difficulty is from the science and technology. Without systematic evaluation based on complex tools, it's neither possible to understand how the air quality will respond the emission reduction, nor to make a scientific strategy on air quality improvement (Zhong et al., 2013; Ponche and Vinuesa, 2005; Vestreng et al., 2007; Wang et al., 2009; Karatzas et al., 2003; Sokhi et al., 2008; Zheng et al.,2009b; Lu et al., 2013). Unfortunately, the capacity building for local environment bureau is still not sufficient to do so. Thus, this study aims to provide an example on how to evaluate 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 prior to other cities (Yuan et al., 2012; Liu et al., 2013; Chan and Yao, 2008; Tan et al., 2009; Verma et al., 2010). On the other hand, Guangzhou is representative because the Asian Games in 2010 has demonstrated the difficulty on reducing $PM_{2.5}$ and O_3 concentration. Guangzhou has made great efforts on controlling emissions during the Asian Games. Although the SO_2, NO_2, VOCs and dust control has efficiently reduced pollutant concentrations, 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 long-term, comprehensive abatement strategy. Thus, a study focusing on the future trend and target achievement strategy is essential to improve the air quality. This experience could be a hint for all China cities that a long-term, well organized emission control plan should be made to control $PM_{2.5}$ and ozone.

Our objective is to provide a full evaluation 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 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 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. In addition, air quality simulation in 2025 was conducted and then compared to NAAQS to infer the impact of emission control plan and to evaluate the accessibility of the new NAAQS. This paper is organized as following: air pollution status, emission controls, air quality improvements, problem remains 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). 10 sites from the Guangzhou (GZ) National Control Network, which was set up by the Guangzhou Environmental Monitoring Center (Fig. 1). Luhu site in urban area belongs to both GZ National Control Network and PRD Regional Air Quality Monitoring Network. In other words, 22 sites were chosen in this study totally. O_3 and PM_{10} are available in all the sites, but only eleven sites in Guangzhou provide data for $PM_{2.5}$ observation (9 sites from Guangzhou National Control Network, 2 sites from GDEMC). (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 concentration lower than the standard are denoted by pink dots, while the other color dots represent the non-attainment. 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 $\mu g\,m^{-3}$. Most sites located along 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 west, though all the highest 8 h value is 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 PRD, sites in Guangzhou and Foshan (GZ and FS) only, representing the heavy polluted area, and sites in surrounding area. For each 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 vary in 7–25 % from May to November. We find that there are 79 % of all the exceedances in all sites happen in summer and fall (June–November). The ratio in Guangzhou and Foshan city regions is as high as 80 %. 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 previous study, strict emission control plan was implemented in Guangzhou since 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 Guangzhou and Foshan urban areas, surrounding area has significant lower O_3 concentration in May to September.

2.2 PM_{10}

The highest daily average, annual average PM_{10} concentration and non-attainment rate are used to describe the PM_{10} pollution status (Fig. 4). The highest PM_{10} daily average concentration in Guangzhou is significantly lower than in 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 result is constant 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. Guangzhou Municipal Government has shut down all the construction sites and increasing frequency of watering roads from once per day to four times per day in 2010.

It should be noted, the new NAAQS proposes stricter annual PM_{10} standard of 70 $\mu g\,m^{-3}$. Most of the sites reported annual average that is lower than the limits. Some sites report the annual average between 70–80 $\mu g\,m^{-3}$ (Fig. 4b). With efforts, the annual PM_{10} concentration is not difficult to be accord with the standard. The problem would be a local issue rather than a regional issue. The highest annual average PM_{10}

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

concentration was observed in Foshan, above 110 µg m^{-3}. The non-attainment rate based on daily PM_{10} concentration is also low in Guangzhou (< 2 % for most sites) in 2010 in Fig. 4c. The risk of high non-attainment rates is still from surrounding area, mainly Foshan. The monthly variation of PM_{10} and $PM_{2.5}$ are combined in the next session.

2.3 $PM_{2.5}$

Other than O_3 and PM_{10}, $PM_{2.5}$ observation is only available from eleven sites in Guangzhou. The highest daily average, annual average $PM_{2.5}$ concentration and non-attainment rate are used to describe the $PM_{2.5}$ pollution status (Fig. 5). Different from PM_{10}, the pressure of $PM_{2.5}$ pollution control is from both high annual average and high daily concentration. The annual average $PM_{2.5}$ concentration is about 30 to 44 µg m^{-3} in Guangzhou, whereas $PM_{2.5}$ could exceed 45 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 15 % and above in south Guangzhou. The highest daily concentrations reach up to 200 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 41 µg m^{-3} in Guangzhou in 2010. To achieve the target of 35 µg m^{-3}, the concentration reduction needs to be at least 15 %.

Monthly variation of $PM_{2.5}$ non-attainment rate is quite similar with PM_{10} variation (Fig. 6). About 70 % of PM_{10} non-attainment days are $PM_{2.5}$ non-attainment days too. The average $PM_{2.5}$ non-attainment rate is about three times compared with PM_{10} non-attainment rates. The $PM_{2.5}$ concentration reduction would be significant effective for PM_{10} attainment, while versa aspect is 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 in November to

March, which accounts for 90 % of all the PM_{10} exceedances in all sites, 91 % in the Guangzhou and Foshan city regions, and 89 % in surrounding area. There are three mechanisms found which may contribute to the high $PM_{2.5}$ concentration and non-attainment rate in Guangzhou. (1) Dirty inland air mass which coming from north. This mechanism is responsible for high pollution episode from October to February when the north winds and northeasterly winds are prevailing. The deteriorated air quality observed in those south sites located in downwind Guangzhou could be a proof (Fig. 6a). (2) Stable wind field and pollutants accumulation mechanism. In March, winds come from north become weaker and push against winds from ocean. Stationary front was formed and contributes to an accumulation environment for precursors. Consequently, the concentration and the non-attainment rate of $PM_{2.5}$ and PM_{10} increase from February to March suddenly, especially the rate of non-attainment. (3) Ozone-$PM_{2.5}$ oxidation mechanism could be found in September. Combined with Fig. 3, the oxidation level of the atmosphere increases with higher O_3 concentration, and convert more SO_2 and NO_x into secondary particulates such as sulfate and nitrite. With O_3 concentrations increased, the mixed air pollutants promote the chemical and photochemical reactions in the air and result in even more complex air pollution. Thus, the $PM_{2.5}$ non-attainment rate is significant but not the PM_{10}. On the other hand, PRD region prevails south winds and southeasterly winds from April to August. Frequent precipitation and sea breeze clean the air particulates in PRD region.

3 Emission controls

3.1 Targets and control principles

To meet people's increasing requirements, the vast majority of cities in China need to achieve the ambient air quality standards in 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 heavy polluted city, should attain the new air quality in 15 yr. Guangzhou EPB also announced targets: try to achieve $PM_{2.5}$ goal in 2020 and make sure to achieve all pollutant targets in 2025.

Guangzhou Municipal government is planning to introduce a series of control measures in the 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 that in last two decades to offset the negative effects of rapid GDP growth on pollution reduction. In this section, we will summarize the measures based on urban development strategy, economy development planning, urban planning, transportation planning and etc.

The major pollution control measures include: (1) a series of policy measures aimed at total emission amount 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 contributive categories of stationary sources of atmospheric pollutants. Among them, emission standards for power plant boilers are in line with the international advanced level (SO_2 concentration $\leq 50\,\mathrm{mg\,m^{-3}}$, NO_x concentration $\leq 100\,\mathrm{mg\,m^{-3}}$, dust $\leq 20\,\mathrm{mg\,m^{-3}}$). (3) Efforts would also be made to drive forward the emission standards for mobile sources. National emission standard IV was 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 would be promoted. (4) Enhance the VOCs emission control based on fuel vapor recovery, coating emission control, solvent usage and replacement, and petrol industry upgrade. (5) Ships emission control and clean fuel process. (6) Dust control. (7) Area source control, including cooking, straw open burning, etc. (8) actively explores the joint prevention and control mechanism for regional atmospheric pollution.

3.2 Emission forecast

Emission amount forecasting includes two parts: emission factors and activity level. The emission factor forecasting is relatively simple, mainly based on the strict emission standards, e.g. Euro 5 standards for vehicles, emission standards for power plant boilers. The activity data forecasting can be summarized into the following categories: (1) based on historical data and trend. This category includes power plant, 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 compared with 2010. Industrial section will increase to 1.03–2.30 times of 2010 level depends on different sectors. In 2025, vehicle population would be 5.97 million, which is 2.82 times of population in 2010. (2) based on specific sector development plan. 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 civil use sources are covered, e.g. consuming products (solvent) usage. The agriculture vehicles are forecasted based on the area of farmland, which would be almost constant since 2010.

Figure 7 provides total emission amount from each category in 2010 and 2025. Both primary $PM_{2.5}$ emissions and other precursors' emission would be reduced. SO_2 emissions would be reduced from 87 thousand tons in 2010 to 25 thousand tons in 2025. The other pollutants would be reduced as well, but not as aggressive as SO_2. The primary $PM_{2.5}$ emission amount would be reduced to 37 % of 2010 level. The emission amount of NO_x, PM_{10}, $PM_{2.5}$ and VOC in 2025 would be controlled to 143, 65, 28 and 188 thousand tons. The detailed sector distribution is provided in Fig. 7.

Sector-based reduction percentage provides an overview of control strategy in each sector in PRD (Fig. 8). Power plants, industry and mobile are three major contributors for all pollutant reductions, which is similar within Guangzhou. There would be 68 %, 43 %, 38 %, 44 % and 29 % reduction on SO_2, NO_x, PM_{10}, $PM_{2.5}$ and VOCs from these three major sectors in PRD region. Products 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 for SO_2 emissions would still be power plants and industry in 2025, though the total amount would be very low. The percentage of particles from dust gets significant because of the decreasing from other sectors. Mobile and biogenic contribution percentages to VOCs would increase, which arouse a further control.

It should be noted here, $PM_{2.5}$ resulted from complicated sources, including primary particulate matters 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 evaluated in previous research, the concentration reductions of $PM_{2.5}$ could only reach 10.2 % with emissions of NO_2 and primary $PM_{2.5}$ reduced by 14.8 % and 17.5 % in Guangzhou (Liu et al., 2013). Thus, precursor emissions must be reduced by more than 15 % in each FYP period, so that a decrease of 15 % in $PM_{2.5}$ concentration (to achieve $35\,\mu g\,m^{-3}$) and a compliance rate of about 80 % around 2025 are attainable in China.

4 Air quality in future

4.1 Air quality models and model evaluation

The MM5-STEM 2K3 modeling system was used in this study. MM5-STEM 2K3 is an integrated model system which combines the STEM-2K3 model and the Penn/NCAR Fifth-Generation Mesoscale Meteorological Model (MM5). It includes the SAPRC99 gaseous mechanism (Carter, 2000) with photolysis rates calculated using the online TUV model (Madronich and Flocke, 1999). The STEM model was evaluated for this region by comparing predicted daily concentrations for November 2010 against observation data measured by the Guangzhou Environmental Monitoring Center and by the Pearl River Delta Regional Air Quality Monitoring Network (Liu et al., 2013). In that study, the Mean Normalized Bias of NO_2, SO_2, PM_{10}, $PM_{2.5}$ and O_3 are ranging from −51 % to 4 %, from −43 % to 29 %, from −56 % to −20 %, from −52 % to −42 %, from −31 % to −6 %, respectively. Meanwhile, the STEM model was also evaluated for PRD regional in November 2006 and November 2009, which yielding the index of agreement (IOA) of SO_2 ranges of 0.86–0.98 in November 2006 and 0.81–0.96 in November 2009 (Wang et al., 2013). The MM5 model was run to produce the meteorological fields to drive the STEM-2K3. The performance of MM5 has been evaluated for both Guangzhou (Chen et al., 2010; Liu et al., 2013) and the other regions in previous researches (Streets et al., 2007).

Two nested domains were used 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 used to drive air quality model for 2010 base case and 2025 scenarios. In this study, January, April, July and October were chosen to simulate as the representative month for each season respectively (Winter, Spring, Summer and Fall) which were also used by Liu et al. (2010a, b) to save the compute 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 other two months in each 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 months simulation 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 can be accepted (Wang et al., 2013 and Liu et al., 2013).

4.2 Air quality improvements

Analysis of air quality from the MM5-STEM model results suggests that the long-term control measures would achieve the $PM_{2.5}$ goal successfully by 2025 (Fig. 10). The annual average concentration would be reduced from 41 µg m^{-3} in 2010 to 21 µg m^{-3} in 2025.

PM_{10} annual average concentration is used to understand the air quality trend since 2000 (Fig. 11). Data before 2012 are observed while the others are estimated. The new NAAQS and CIP would be milestone for air quality improvement in Guangzhou. The PM_{10} annual average concentration increased from 2000 to 2003 and decreased during 2005 to 2008. After 2008, the concentrations are stable until 2012. With implementation CIP since 2013, the PM_{10} concentration would start decreasing again. The annual average concentration of PM_{10} could be lower than 40 µg m^{-3} in 2025.

4.3 Problem remains

Under current strategy, the O_3 control would be problematic. The average non-attainment rate of maximum 8 h average concentration would be increased from 7.1 % in 2010 to 12.9 % in 2025 (Fig. 12). In some monitoring site, the non-attainment rate in 2025 would reach as high as 19.6 %, similar with the worst month in 2010. Ozone pollution will remain the most primary atmospheric environmental problem facing Guangzhou for quite a long period of time.

In accordance with the previous analysis, Guangzhou needs to make improvements in regulations, management mechanism, capacity building, and control measures in order to achieve the goal of air quality improvement. In terms of sources, as industrial pollution control deepens, prominence should also be given to non-point sources such as small and medium-sized boilers, dust, food and beverage fumes and decoration spraying, as well as motor vehicles and other mobile sources. The next section will discuss the implication of O_3 control from international experience.

5 Implication of ozone control from south California practices

5.1 Similar gaps and schedule

Guangzhou and California share a lot of similarity on air pollution control about their causes and pollution characteristics to some extent. Both of them are most important economic hubs and bear high ozone concentration. The Gross Domestic Product (GDP) in Guangdong was about $800 billion, contributing 10.9 % of the national total and ranking the first in China. According to the statistics 2010, the GDP of California reached $1936.4 billion, accounting for 13.34 % of the United States and the highest in the Nation. In past decade, the growth of Guangdong economy and vehicles is very similar with the urban sprawl in California after the World War II. The annual GDP grew at a rate of over 10 %, accompanied by rapid growth of vehicles population (13.5 % annually) and fuel consumption.

Accompanying with these increases is the emerging of severe air pollution. For both statistics, southern California keeps the highest values in violation of the new 8 h standard in US from 1980 to 1998. However, with continuous efforts, the air quality made great progress in California. However, PRD is facing even more serious challenges, due much to the late start of air quality management, the continuously soaring economy, and numerous manufacturing factories. This section provides two implications from California based on historical data analysis.

5.2 Implication I: scientific ratio of VOC / NO_x reduction

During 1988 through 2007 in California, statewide maximum 8 h ozone values decreased 47 %, and maximum 8 h carbon monoxide values dropped 73 % (Fig. 13). These air quality improvements occurred at the same time the State's population increased 33 % and the average daily VMT increased 46 %. Emissions of NO_x and Reactive Organic Gases (ROG) in California were about 4744 and 5990 $t\,day^{-1}$ in 1985 and the ROG / NO_x ratio is about 1.3. In 2005, the amount of NO_x and ROG emissions were reduced to 3513 and 2455 $t\,day^{-1}$ (ROG / NO_x ratio 0.7). On a statewide basis, NO_x emissions decline by 26 % (1231 $t\,day^{-1}$) between 1985 and 2005. Emissions of ROG in California decreased by 59 % (3535 $t\,day^{-1}$) from 1985, which is about double percentages of NO_x reduction. In addition, before this big step, emissions of NO_x in California keep stable between 1975 and 1985, only decreased by 3 %, while the emissions of ROG decreased 15 % between 1975 and 1985.

Emissions of NO_x and VOCs in Guangzhou are about 2834 and 3355 $t\,day^{-1}$ in 2010, as shown in Fig. 7. Table 1 summarizes the controls in California and Guangzhou. The VOCs / NO_x ratio is about 1.1, similar with California in 1985. The difference is, in California the VOCs / NO_x ratio was successfully reduced to 0.7 in twenty years, while this ratio would be increased to 1.3 in Guangzhou in fifteen years from 2010 as forecasted. As a result, Guangzhou needs very strong control on VOCs to reduce its ozone. As a conclusion, the VOC / NO_x reduction ratio should reach at least 2 : 1 (in California, it is about 3 : 1) to reduce O_3.

5.3 Implication II: VOCs control sectors

The sector distribution of VOCs emissions in California is further investigated to find out the reduction potential. Figure 14 is a statewide ROG emission trends referenced from 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 emission. The use of improved evaporative emission control systems (On-board Refueling Vapor Recovery, ORVR) has been reduced refueling and diurnal emissions effectively. The computerized fuel injection, engine management systems to meet increasingly stringent California emission standards, cleaner gasoline, and the Smog Check program are also contributing to the ROG reduction. ROG emissions 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.

Guangzhou government has taken some of the measures to reduce its VOCs emissions. The next step should enhance the following aspects: 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 so on.

5.4 Implication III: ozone transport

Since 1989, 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 exception of San Diego. Areas impacted by overwhelming transport, although designated nonattainment, are not able to achieve the air quality goals because local control strategies in these areas would not be effective in reducing ozone concentrations. However, these areas are subject to many local control strategies, such as cleaner fuels and low emission vehicles (Keating and Farrell, 1999).

In the future, regional ozone air quality plans in Guangzhou must be taken 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 trend suggests that several straightforward, feasible and practical measures can be taken to dramatically improve air quality 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 rationalize its public policy decisions and investments. Streamlining regulatory authority and enforcement will ensure effective execution, from the national government all the way down to the factory floor. The air quality problem would be partly solved in the coming 15 yr, not all of them. Ozone would be an issue on the new NAAQS compliance. The key solution would be VOCs emission reduction from multi-sectors.

Acknowledgements. This research was supported by the key project of the Natural Science Foundation of Guangdong Province (S2012020011044) and Guangzhou Environmental Protection Bureau. The authors thank Junyu Zheng of South China University of Technology for providing PRD emission inventory. We also thank Guangzhou Environmental Monitoring Center for providing meteorology and ambient air quality observation data. Huan Liu is supported by the NSFC (71101078), the special fund of State Key Joint Laboratory of Environment Simulation and Pollution Control. The work was also supported by the high-performance grid computing platform of Sun Yat-sen University. The contents of this paper are solely the responsibility of the authors and do not necessarily represent the official views of the sponsors.

References

Carter, W.: Documentation of the SAPRC-99 Chemical Mechanism for VOC Reactivity Assessment, 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. Circum., 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., Walsh, M., He, K., Witherspoon, C., Yang, J., Drueke, M., Tang, D., and Amann, M.: Regional Air Quality Integrated Control System Research, CCICED Special Policy Study, Beijing, 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. Modell. Softw., 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.

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., Cheng, S., Xing, J., Zhang, Q., Streets, D. G., Jang, C., Wang, W., and Hao, J.: Understanding of regional air pollution over China using CMAQ, part I performance evaluation and seasonal variation, Atmos. Environ., 44, 2415–2426, 2010a.

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, part II process analysis and sensitivity of ozone and particulate matter to precursor emissions, Atmos. Environ., 44, 3719–3727, 2010b.

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, Springer, Heidelberg, 1999.

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. Policy, 48, 779–789, 2012.

Sokhi, R. S., Mao, H., Srimath, S. T. G., Fan, S., Kitwiroon, N., Luhana, L., Kukkonen, J., Haakana, M., Karppinen, A., Dick van den Hout, K., Boulter, P., McCrae, I. S., Larssen, S., Gjerstad, K. I., San José, R., Bartzis, J., Neofytou, P., van den Breemer, P., Neville, S., Kousa, A., Cortes, B. M., and Myrtveit, I.: An integrated multi-model approach for air quality assessment: development and evaluation of the OSCAR Air Quality Assessment System, Environ. Modell. Softw., 23, 268–281, 2008.

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.

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.

Vestreng, V., Myhre, G., Fagerli, H., Reis, S., and Tarrasón, L.: Twenty-five years of continuous sulphur dioxide emission reduction in Europe, Atmos. Chem. Phys., 7, 3663–3681, doi:10.5194/acp-7-3663-2007, 2007.

Wang, L., Jang, C., Zhang, Y., Wang, K., Zhang, Q., Streets, D., Fu, J., Lei, Y., Schreifels, J., He, K., Hao, J., Lam, Y.-F., Lin, J., Meskhidze, N., Voorhees, S., Evarts, D., and Phillips, S.: Assessment of air quality benefits from national air pollution control policies in China, Part I: Background, emission scenarios and evaluation of meteorological predictions, Atmos. Environ., 44, 3442–3448, 2010a.

Wang, L., Jang, C., Zhang, Y., Wang, K., Zhang, Q., Streets, D., Fu, J., Lei, Y., Schreifels, J., He, K., Hao, J., Lam, Y.-F., Lin, J., Meskhidze, N., Voorhees, S., Evarts, D., and Phillips, S.: Assessment of air quality benefits from national air pollution control policies in China, Part II: Evaluation of air quality predictions and air quality benefits assessment, Atmos. Environ., 44, 3449–3457, 2010b.

Wang, S., Xing, J., Chatani, S., Hao, J., Klimont, Z., Cofala, J., and Amann, M.: Verification of anthropogenic emissions of China by satellite and ground observations, Atmos. Environ., 45, 6347–6358, 2011.

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., 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. Policy, 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. 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.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
I◀ | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 1. Comparison of VOCs and NO_x emissions control in California and Guangzhou.

Emission	California	Guangzhou
VOCs emission / NO_x emission	1.3 (1985)	1.2 (2010)
VOCs emission / NO_x emission	0.7 (2005)	1.5 (2025)
VOCs reduction amount / NO_x reduction amount	3 : 1	0.8 : 1

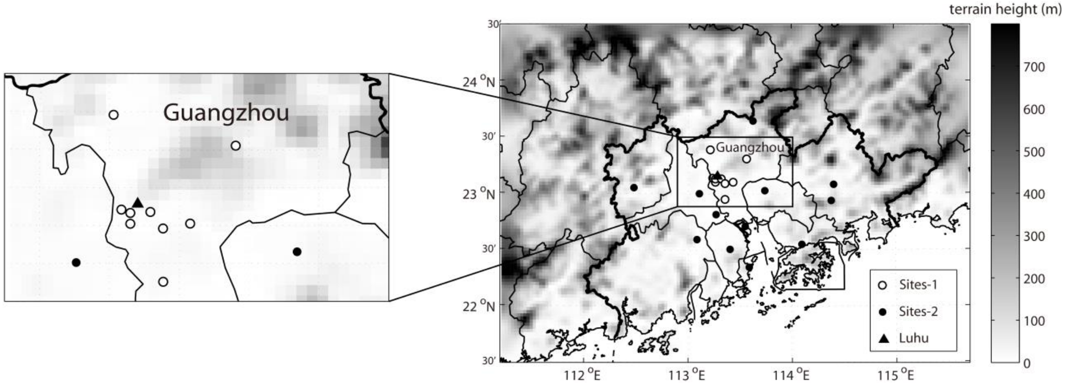
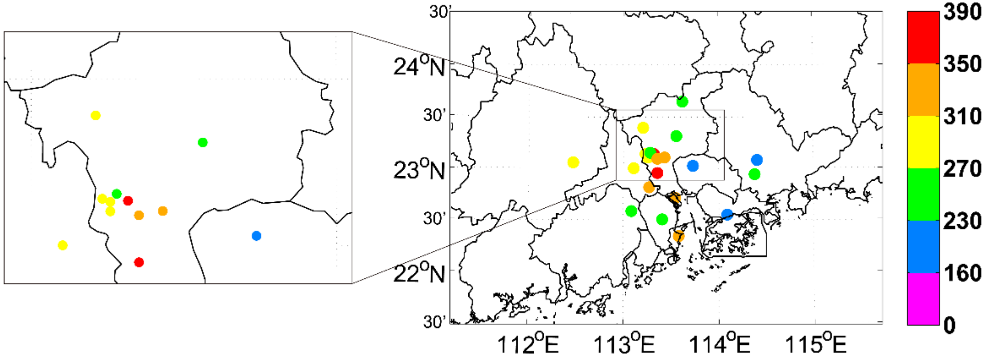


Fig. 1. Geographical map of Pearl River Delta region and location of air quality monitoring sites. (Sites-1: sites from Guangzhou National Control Network; Sites-2: sites from PRD Regional Air Quality Monitoring Network; Luhu: Luhu site.)

(a) O_3 Annual Highest 8–Hour Average



(b) O_3 Annual Highest 1–Hour Average

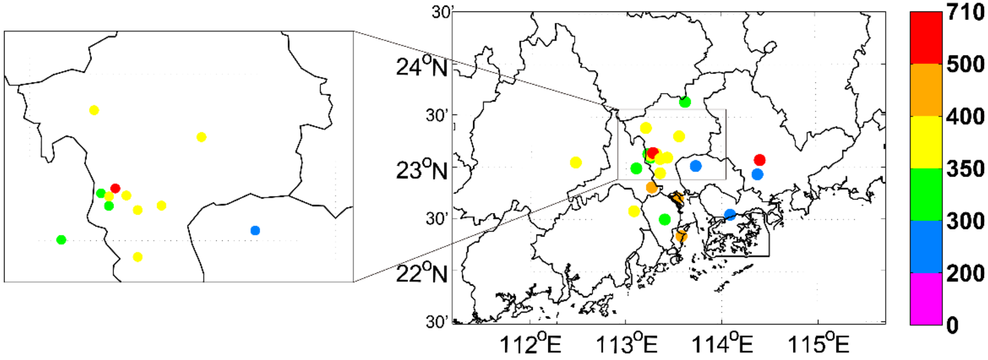


Fig. 2. Ozone concentration (μg m^{-3}) of each of the 22 individual sites in PRD region in 2010 of **(a)** the annual highest daily maximum 8 h average and **(b)** the annual highest 1 h average.

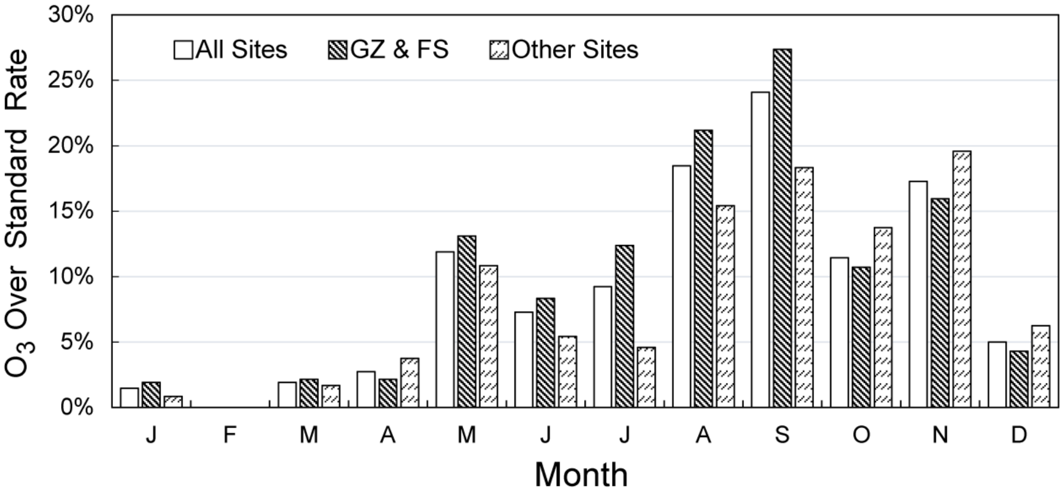


Fig. 3. Average fraction of days per month whose daily maximum 8 h average exceeds 160 µg m^{-3} out of all days per month with ozone data.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◂◂
▸▸
◂
▸
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

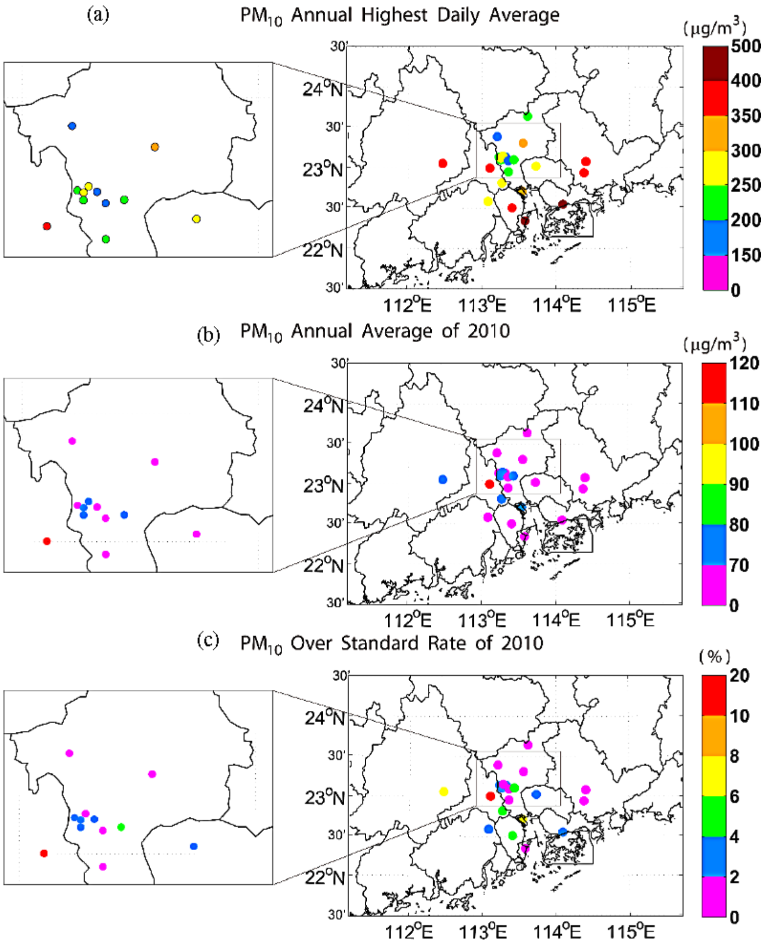


Fig. 4. PM_{10} concentration ($\mu g\,m^{-3}$) of each of the 22 individual sites in PRD region in 2010 of **(a)** the annual highest daily average, **(b)** the annual average and **(c)** non-attainment rate.

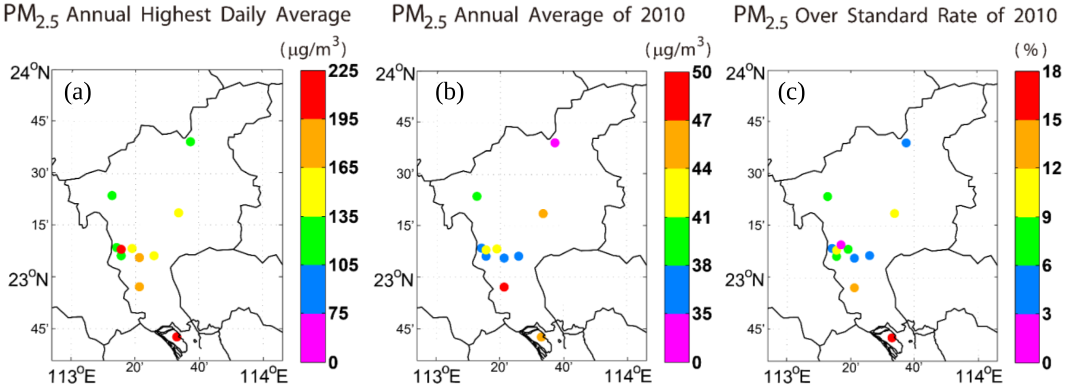


Fig. 5. $PM_{2.5}$ concentration (µg m^{-3}) of each of the eleven individual sites in Guangzhou region in 2010 of **(a)** the annual highest daily average, **(b)** the annual average and **(c)** over standard rate.

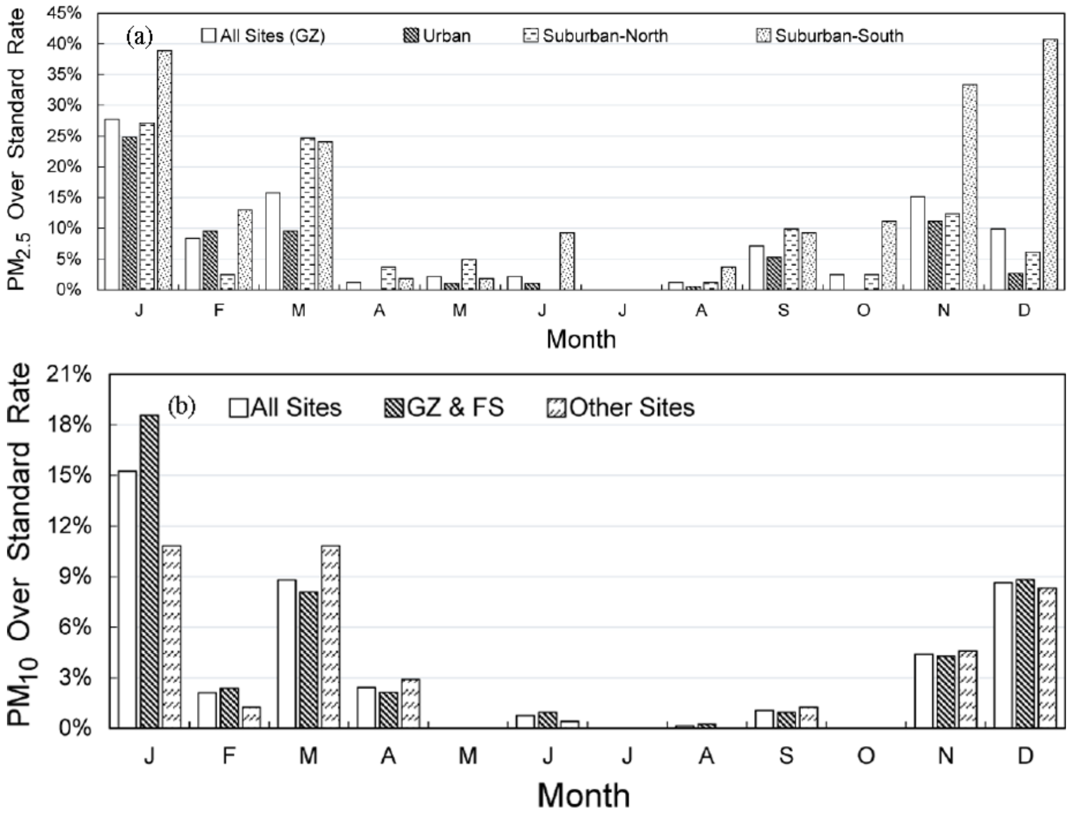


Fig. 6. Percentage of $PM_{2.5}$ or PM_{10} non-attainment days per month in 2010 **(a)** $PM_{2.5}$ in Guangzhou and **(b)** PM_{10} in PRD.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▎
▶▎
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

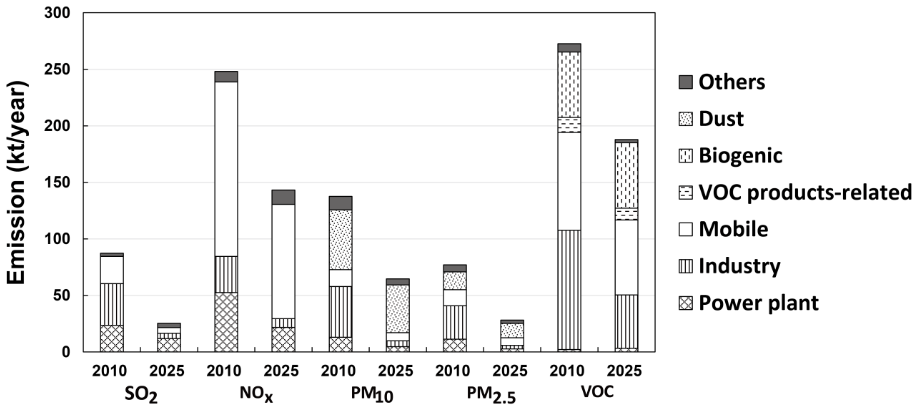


Fig. 7. Total emission amount from each category in 2010 and 2025.

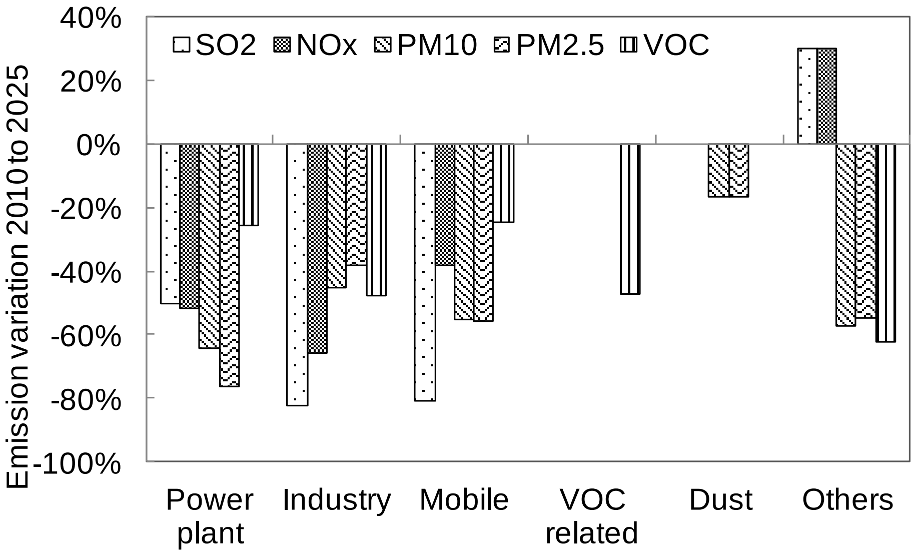


Fig. 8. Sector based emission reduction percentage in 2025.

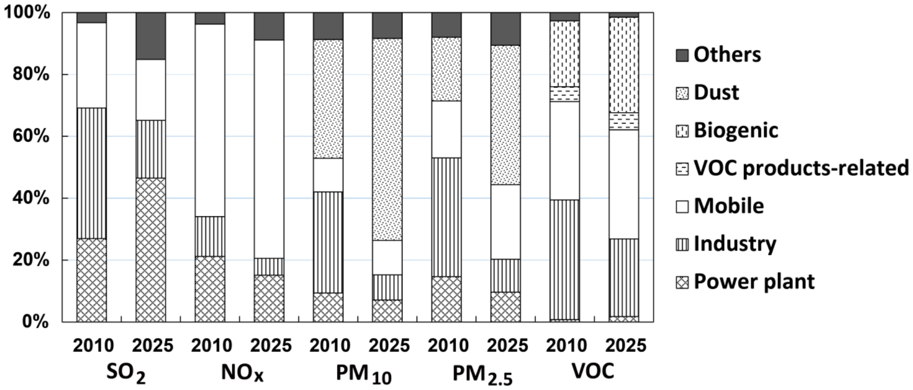


Fig. 9. Comparison of sector contribution between 2010 and 2025.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

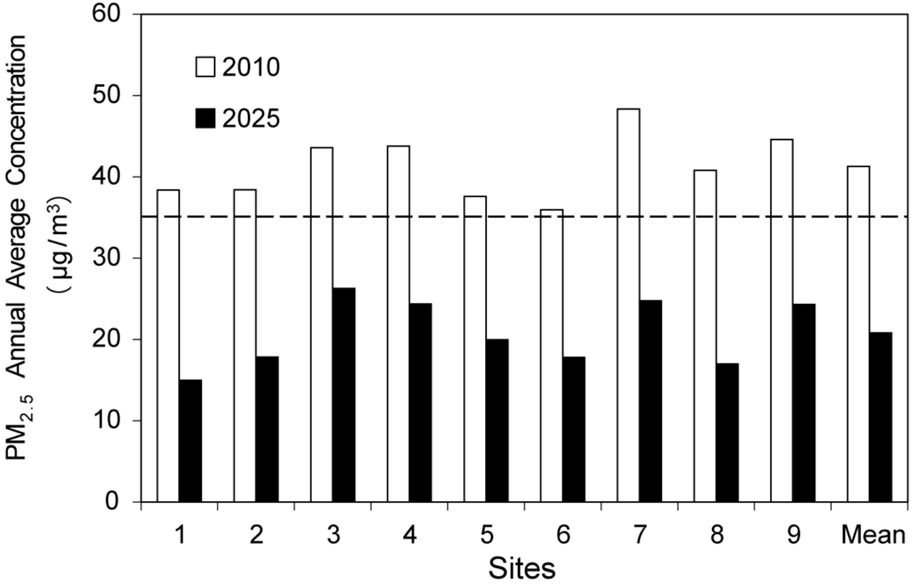


Fig. 10. $PM_{2.5}$ annual average concentration ($\mu g\,m^{-3}$) in Guangzhou, 2010 and 2025. (Sites name from 1 to 9: Guangya, 5School, Jiancezhan, Tianhu, Guangshan, 86School, Panyu, Huadu, Jiulong).

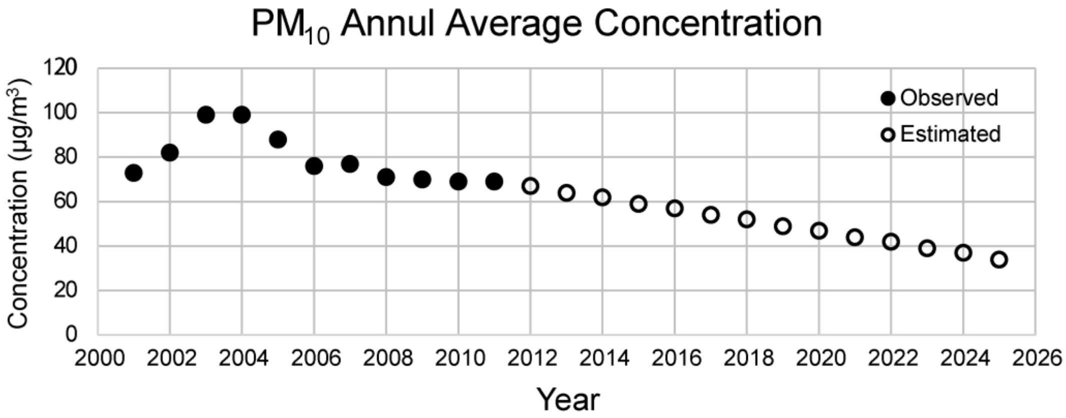


Fig. 11. Long-term PM_{10} annual average concentration ($\mu g\, m^{-3}$) trend in Guangzhou, 2000–2025.

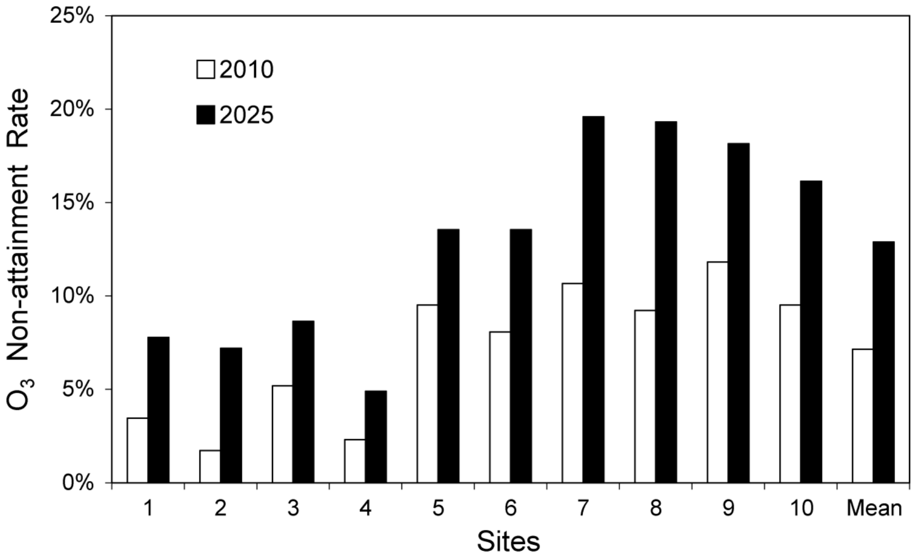


Fig. 12. Ozone non-attainment rate (by maximum 8 h average concentration) in Guangzhou, 2010 and 2025. (Sites name from 1 to 10: Guangya, 5School, Jiancezhan, Tianhu, Luhu, Guangshan, 86School, Panyu, Huadu, Jiulong).

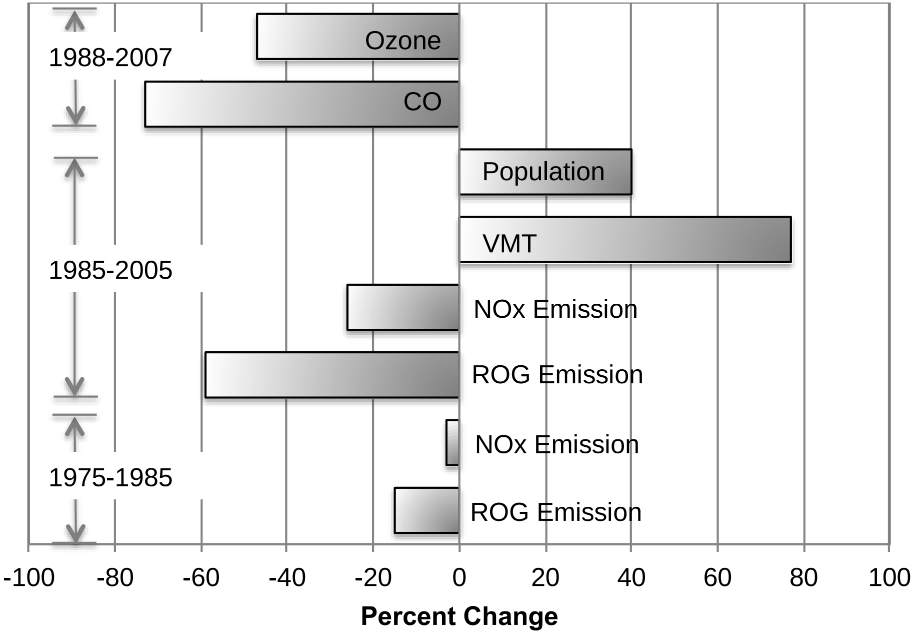


Fig. 13. Percent change in air quality, growth and emissions in California. The California Air Resources Board's (ARB's) Emission Inventory Branch (EIB) uses the term Reactive Organic Gases (ROG) instead of VOC in this almanac.

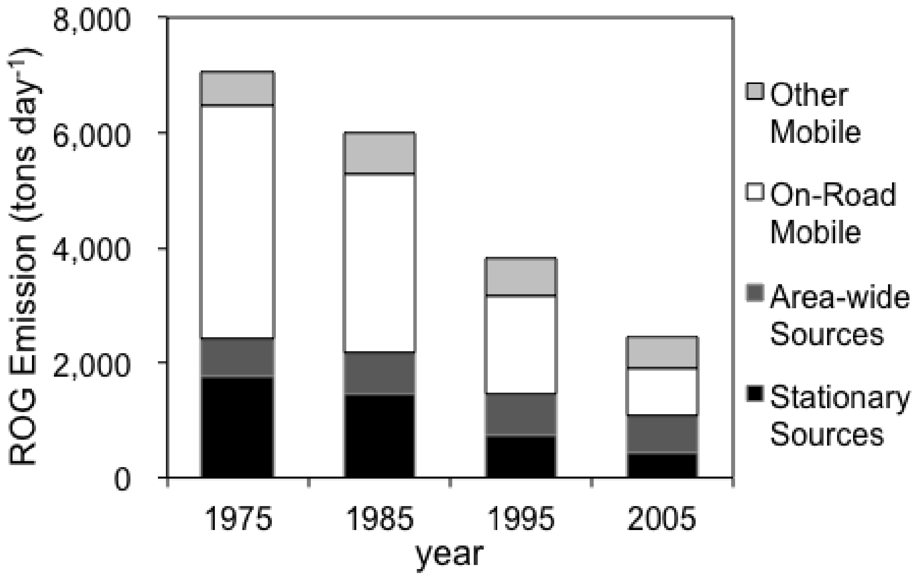


Fig. 14. ROG emissions by sectors in California.