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Research article

Effects of air pollution control measures on air quality improvement in Guangzhou, China

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A R T I C L E I N F O

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A B S T R A C T

The ambient air quality of Guangzhou in 2016 has significantly improved since Guangzhou and its surrounding cities implemented a series of air pollution control measures from 2014 to 2016. This study not only estimated the effects of meteorology and emission control measures on air quality improvement in Guangzhou but also assessed the contributions of emissions reduction from various sources through the combination of observation data and simulation results from Weather Research and Forecasting - Community Multiscale Air Quality (WRF-CMAQ) modeling system. Results showed that the favorable meteorological conditions in 2016 alleviated the air pollution. Compared to change in meteorology, implementing emission control measures in Guangzhou and surrounding cities was more beneficial for air quality improvement, and it could reduce the concentrations of SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3 by 9.7 $\mu g\, m^{-3}$ (48.4%), 9.2 $\mu g\, m^{-3}$ (17.7%), 7.7 $\mu g\, m^{-3}$ (14.6%), 9.7 $\mu g\, m^{-3}$ (13.4%), and 12.0 $\mu g\, m^{-3}$ (7.7%), respectively. Furthermore, emission control measures that implemented in Guangzhou contributed most to the concentration reduction of SO_2, NO_2, $PM_{2.5}$, and PM_{10} (46.0% for SO_2, 15.2% for NO_2, 9.4% for $PM_{2.5}$, and 9.1% for PM_{10}), and it increased O_3 concentration by 2.4%. With respect to the individual contributions of source emissions reduction, power sector emissions reduction showed the greatest contribution in reducing the concentrations of SO_2, NO_2, $PM_{2.5}$, and PM_{10} due to the implementation of Ultra-Clean control technology. As for O_3 mitigation, VOCs product-related source emissions reduction was most effective, and followed by transportation source emissions reduction, while the reductions of power sector, industrial boiler, and industrial process source might not be as effective. Our findings provide scientific advice for the Guangzhou government to formulate air pollution prevention and control policies in the future.

1. Introduction

Over the past two decades, China has been suffering from severe air pollution, particularly $PM_{2.5}$ and O_3, which has posed a threat to human health (Dan et al., 2004; Gautam et al., 2016, 2018; Maji et al., 2019; Song et al., 2016) and attracted a great attention from the government and public (Cheng et al., 2018; Fontes et al., 2017; Huang et al., 2014; Tan et al., 2018). To mitigate air pollution in China, both national and regional governments have promulgated a series of air pollution control strategies. For instance, the China State Council released the Air Pollution Prevention and Control Action Plan (APPCAP) in 2013, which set specific targets for $PM_{2.5}$ reduction in three major metropolitan clusters, among which a 15% reduction goal for 2017 was specified for the Pearl River Delta (PRD, including nine cities: Guangzhou, Zhaoqing, Jiangmen, Foshan, Zhongshan, Zhuhai, Shenzhen, Dongguan, and Huizhou) region (The Central People's Government of the People's Republic of China, 2013). In the following year of 2014, the Guangdong provincial government issued the Guangdong Air Pollution Prevention and Control Action Plan (GDAPPCAP) to control regional pollution, and the goals specified the annual average concentrations of SO_2, NO_2, and PM_{10} in the cities of the PRD region should attain the second-level concentration limit of the China National Ambient Air Quality Standards (NAAQS) in 2017, and the annual average concentration of $PM_{2.5}$ should decrease by 15%, excluding 20% special mitigation target for

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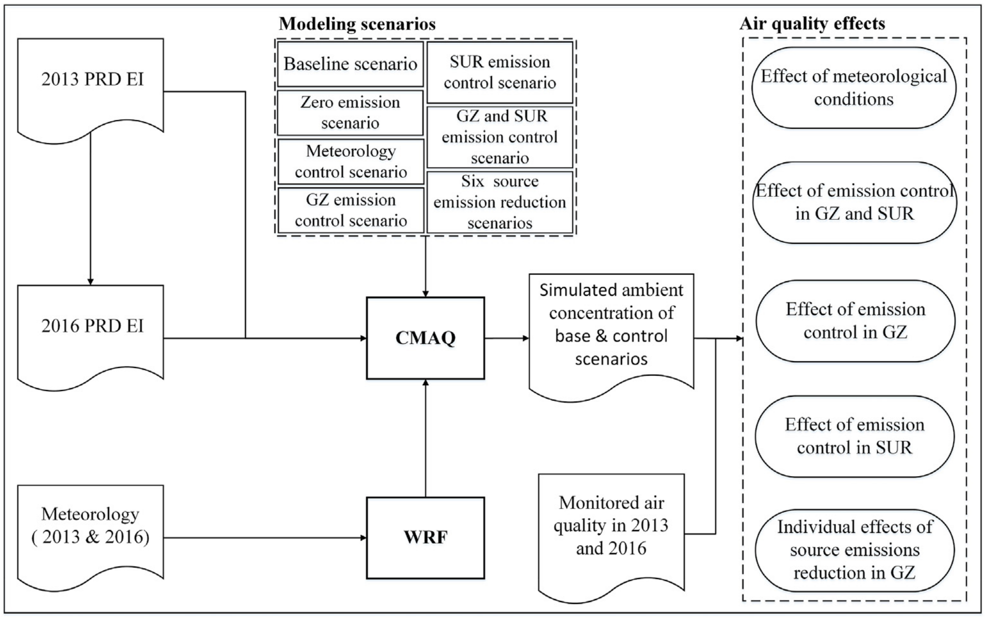

Fig. 1. The conceptual framework for the evaluation of air quality effects. PRD: Pearl River Delta, EI: emission inventory, GZ: Guangzhou, SUR: surrounding cities.

Guangzhou, Foshan, and Dongguan (People's Government of Guangdong Province, 2014).

In order to achieve the national and provincial air quality goals, Guangzhou, as the capital city of Guangdong Province and the metropolis of PRD, has carried out a series of air pollution control measures which were listed in the Guangzhou Air Pollution Prevention and Control Action Plan (Action Plan) from 2014 to 2016 (GZEP, 2014). Similar to the classification of control measures in the GDAPPCAP, the control measures in the Action Plan were classified into seven target pollutant sources: power sector, industrial boiler, industrial process source, transportation source, dust source, VOCs product-related source, and other sources. Table S1 summarized the control measures for each pollutant source in the Action Plan and GDAPPCAP. It appears that the control measures implemented for certain pollutant sources in Guangzhou were more stringent than those in Guangdong province, which resulted in slightly larger emissions reduction ratios of air pollutants in Guangzhou compared to the surrounding cities (e.g., Shenzhen, Foshan, etc.). For example, Guangzhou was required to implement the Ultra-Clean Emissions Work Plan in power sector, while Guangdong only needed to implement the general desulfurization and denitrification measures for SO_2 and NO_2, and the special emission limit for smoke dust in Emission Standard of Air pollutants of Thermal Power Plants (GB13223-2011). The observed annual average concentrations of SO_2, NO_2, PM_{10}, $PM_{2.5}$ and the annual 90th percentile of maximum daily 8-hr averaged O_3 concentration (Annual 90th per MDA8 O_3, which was calculated by the method in supplementary material Section S1) at air-monitoring sites at Guangzhou in 2016 were $12\,\mu g\,m^{-3}$, $46\,\mu g\,m^{-3}$, $56\,\mu g\,m^{-3}$, $36\,\mu g\,m^{-3}$ and $155\,\mu g\,m^{-3}$, which decreased by 40.0%, 11.5%, 22.2%, 32.1% and 0.6% compared with that in 2013. The improved air quality of Guangzhou revealed that the above emission control measures have made significant achievements, while the annual average concentrations of NO_2 and $PM_{2.5}$ in 2016 still exceeded the corresponding annual limit values ($40\,\mu g\,m^{-3}$ and $35\,\mu g\,m^{-3}$ for NO_2 and $PM_{2.5}$, respectively). However, it was still unclear that how effective these control measures were in improving air quality in Guangzhou, and it was also unclear that which control measures were more effective.

A number of studies have been conducted to investigate and evaluate the effects of emission control strategies on air quality (Cheng et al., 2011; Wang et al., 2017b, 2019a, 2019b; Zhang et al., 2018). Tan et al. (2017) and Wang et al. (2014) conducted the assessment on the effectiveness of emission control policies for the control of SO_2 and NO_x during the 11th and 12th Five-Year Plans (2006–2015). Cai et al. (2017) and Cai et al. (2018) evaluated the effect of the APPCAP on $PM_{2.5}$ concentration in the target year of 2017, 2020, and 2030. The aforementioned studies commonly concentrated on the assessment of long-term effects over particular air pollutants of interest rather than multi-pollutants simultaneously. Several studies also estimated the contributions of control measures for various sources to air pollution alleviation, but most of them focused on short-term air pollution episodes continuing for several days to weeks (Jia et al., 2017; Liu et al., 2013; Wang et al., 2016b, 2017a). To our knowledge, there is no comprehensive investigation yet on the long-term effects of air pollution control measures at the city level in China, especially in PRD.

This study integrated observational data and air quality model simulations to evaluate (1) the effects of meteorology, joint emissions control, local emissions control, and surrounding area emissions control on air quality improvement, and (2) the effects of emissions reduction from various sources on air pollution abatement in Guangzhou. Our results first revealed the importance of emission control measures in Guangzhou, and then identified which control measures can be more effective as well as their projected air quality improvement. These results together provide scientifically sound recommendations to the decision makers for designing effective air pollution control policies in Guangzhou.

2. Methodology

An overview of the analysis process for evaluating the air quality effects was provided in Fig. 1. Firstly, the emission inventory (EI) of PRD in 2016 was updated from 2013 according to the change of activity data and implementation of pollution control measures. Secondly, in order to distinguish the effects of meteorological conditions and emission control measures, four simulation scenarios, including meteorology scenario, Guangzhou and surrounding emission control scenario, Guangzhou emission control scenario, surrounding emission control scenario, were designed by changing EI or meteorology. Furthermore, six source emission reduction scenarios were designed to evaluate the individual contributions of source emissions reduction. In each source emission reduction scenario, we removed emissions reduction from a controlled pollutant source, including power sector, industrial boiler, industrial process source, transportation source, dust source, and VOCs

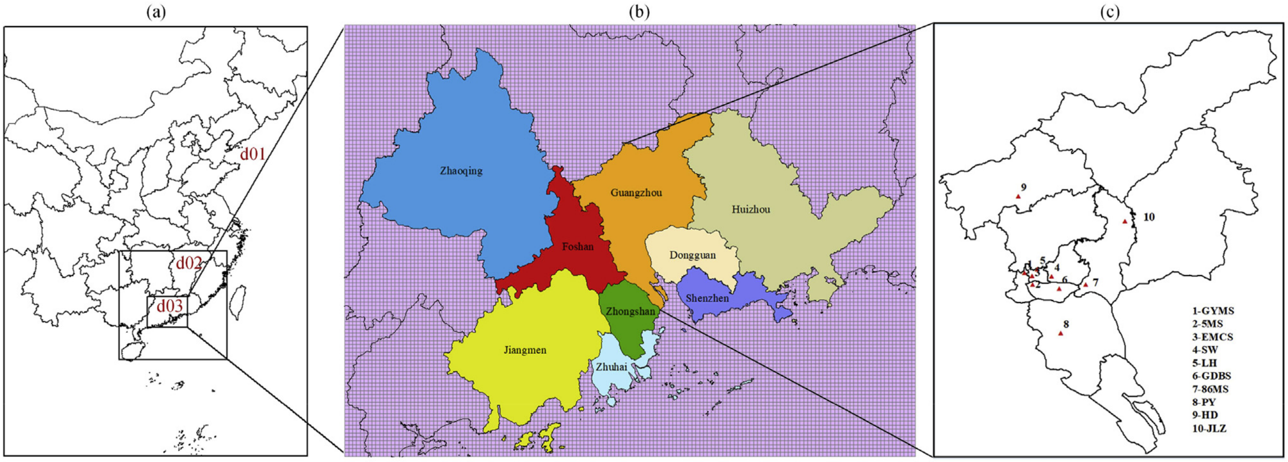

Fig. 2. (a) The three nested modeling domains at 27 km (d01), 9 km (d02), and 3 km (d03); (b) Inner 3-km domain; (c) Locations of ten sites in Guangzhou. GYMS: Guangya middle school, 5MS: 5th middle school, EMCS: Environmental monitoring center station, SW: Sports west, LH: Luhu, GDBS: Guangdong business school, 86MS: 86th middle school, PY: Panyu, HD: Huadu, JLZ: Jiulongzhen.

product-related source. Thirdly, the Weather Research and Forecasting Model (WRF) was used to simulate the meteorological conditions in 2013 and 2016 to drive Community Multiscale Air Quality Model (CMAQ) air quality simulations under various simulation scenarios. Finally, the simulated air quality and the monitored air quality were combined to analyze not only the effects of meteorological conditions, Guangzhou and surrounding emissions control, Guangzhou emissions control, and surrounding area emissions control on the air quality of Guangzhou but also the effects of emissions reduction from various sources. Further details of the process were provided below and in the Supplementary Material.

2.1. Study domain

Three nested domains were applied for CMAQ and WRF in this study (Fig. 2a), with a horizontal resolution of 27 km, 9 km, and 3 km, respectively. Vertically, twenty sigma layers from the surface to the tropopause were set for all domains. The outer 27-km domain covers most of China and some other parts of Asia with 175 × 124 grid cells. The initial and boundary conditions for the CMAQ simulation on the outer domain were based on default profiles in the CMAQ model. The middle 9-km domain aims to cover southeastern China with 133 × 133 grid cells, including Guangdong province. The innermost domain covering the whole PRD region with 112 × 148 grid cells is the focus of this study (Fig. 2b). Boundary conditions for the middle domain and innermost domain were generated from simulation results on the outer domain and middle domain, respectively. On the basis of CMAQ domain, three lines were added to the above and the below domain of CMAQ, and three columns were added to the left and right domain of CMAQ, then the WRF model domain was obtained.

2.2. Emission inventory and emission reduction

The anthropogenic EIs for the outer and middle domains were provided by Tsinghua University (Ma et al., 2017). For the innermost domain, two basic EIs were adopted: 2013 PRD EI and 2016 PRD EI. This paper updated the EI in 2016 from 2013, which was developed by the joint research team of Tsinghua University and South China University of Technology. A technology-based emission factor method was applied to calculate the emissions of each source in each city from activity data (e.g., energy consumption, industrial products, solvent use, etc.), technology-based uncontrolled emission factors, and penetrations of control technologies (Wang et al., 2011; Zhao et al., 2013; Zheng et al., 2018). The activity data were derived from Guangdong Statistical Yearbook, Guangdong Rural Statistical Yearbook, and China Energy Statistical Yearbook (GDSB, 2017a; 2017b; NBS, 2017). The uncontrolled emission factors were acquired from technical guidelines and literature (MEE, 2014; Zhong et al., 2018). The penetrations of control technologies were updated for 2016 according to environmental statistics from the Environmental Protection Bureau of each city in PRD and the evolution of emission standards (GDEEP, 2014; People's Government of Guangdong Province, 2011). The PRD anthropogenic emissions of SO_2, NO_x, $PM_{2.5}$, PM_{10}, VOCs, and CO in 2016 were estimated to be 151 kt, 375 kt, 165 kt, 592 kt, 889 kt, and 2160 kt, respectively. Compared with that in 2013, the emissions of Guangzhou reduced by 57.3% for SO_2, 35.9% for NO_x, 32.1% for $PM_{2.5}$, 23.0% for PM_{10}, 36.4% for VOCs, and 29.2% for CO. Emissions in the eight surrounding cities reduced by 31.0% for SO_2, 32.1% for NO_x, 23.6% for $PM_{2.5}$, 11.9% for PM_{10}, 22.7% for VOCs, and 22.1% for CO (Fig. 3). As shown in Fig. 3, although the total emissions reductions for all air pollutants in Guangzhou were lower than that in surrounding cities, the emissions reduction ratios were higher. In addition, the natural EIs were calculated by the Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1) (http://lar.wsu.edu/megan/guides.html), which has been widely tested (Gao et al., 2016, 2017). Multiple variables, including land cover data (e.g., leaf area index (LAI) and plant functional type (PFT)) and meteorological conditions (e.g., hourly temperature, solar radiation, humidity, wind speed, and soil moisture) (Guenther et al., 2012), were used to driven MEGAN2.1.

Fig. 4 showed the proportions of emissions reduction from various sources in the total emissions reductions of air pollutants in Guangzhou between 2013 and 2016. Power sector dominated SO_2 emissions reduction, which accounted for 79.1% of total emissions reduction. Industrial boiler, other sources, and industrial process source contributed 13.7%, 5.2%, and 2.0% to total SO_2 emissions reduction, respectively. It is evident that power sector also dominated NO_x emissions reduction. Furthermore, transportation source, industrial boiler, other sources, and industrial process source contributed 18.8%, 15.0%, 7.0%, and 1.4% to total NO_x emissions reduction. For $PM_{2.5}$, power sector and industrial boiler were the two most important contributors, contributing 47.6% and 26.3% of total emissions reduction. Transportation source, other sources, industrial process source, and dust source contributed 8.7%, 8.7%, 6.0%, and 2.7% to total $PM_{2.5}$ emissions reduction. Power sector (42.6%), industrial boiler (24.5%), and dust source (17.9%) were the top three contributors for total PM_{10} emissions reduction. VOCs product-related source and transportation source contributed most to VOCs emissions reduction, and they constituted 72.8% and 25.0% of total VOCs emissions reduction. Transportation source

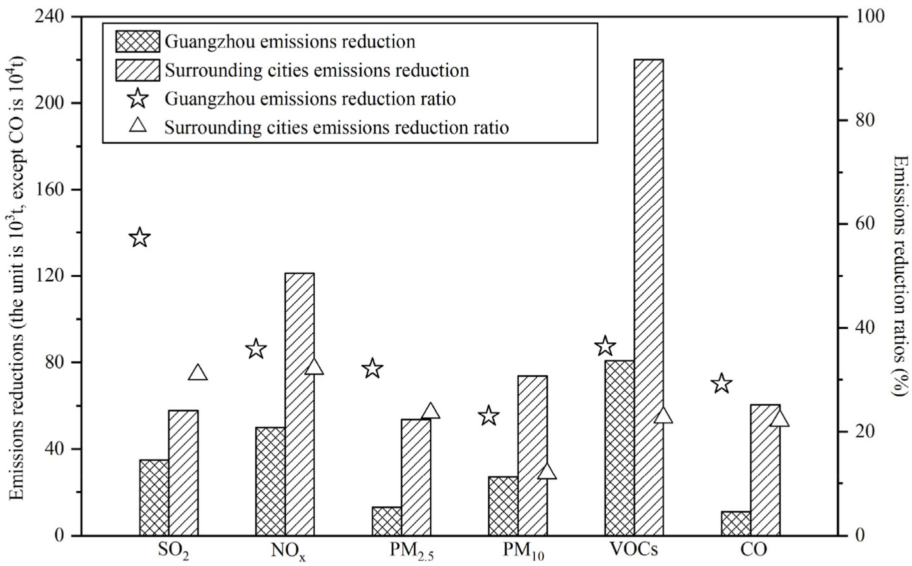

Fig. 3. Total emissions reductions and emissions reduction ratios for SO_2, NO_x, $PM_{2.5}$, PM_{10}, VOCs, and CO in Guangzhou and surrounding cities by comparing emissions in 2013 and 2016.

and industrial boiler made up 84.9% and 13.8% of total CO emissions reduction.

2.3. Model description and configuration

An integrated modeling system, which combined CMAQ version 5.2 (CMAQv5.2) and WRF version 3.9.1 (WRFv3.9.1), was used to evaluate the air quality effects. The WRFv3.9.1, which consists of three major programs: WRF Preprocessing System (WPS), OBSGRID, and WRF Model, was applied to simulate the meteorological field (NCAR, 2017). The NCEP FNL (Final) Operational Global Analysis data downloaded from http://dss.ucar.edu/datasets/ds083.2/were used to drive the WRFv3.9.1. Output files from WRFv3.9.1 were post-processed by CMAQv5.2 using Meteorology Chemistry Interface Processor (MCIP) program. The CMAQv5.2 was applied to predict the ambient concentrations, including the concentrations of SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3. The four main CMAQv5.2 components are MCIP, initial conditions processor (ICON), boundary conditions processor (BCON), and CMAQ chemistry-transport model (CCTM) (U.S.EPA, 2017). Furthermore, the Carbon Bond Mechanism (CB6) with aqueous and aerosol extensions and the AREO5 aerosol mechanism were selected for the gas-phase chemistry module and the aerosol module in CMAQv5.2, respectively. The detailed description of major components and operating steps of WRFv3.9.1 and CMAQv5.2 can refer to Fig. S1. In this study, the local ten national-controlled air-monitoring sites (Fig. 2c) were chosen to represent the whole of Guangzhou city when analyzing the air quality effects.

2.4. Modeling scenarios

To investigate the effects of meteorological conditions and control measures on air quality improvement in Guangzhou, the following five

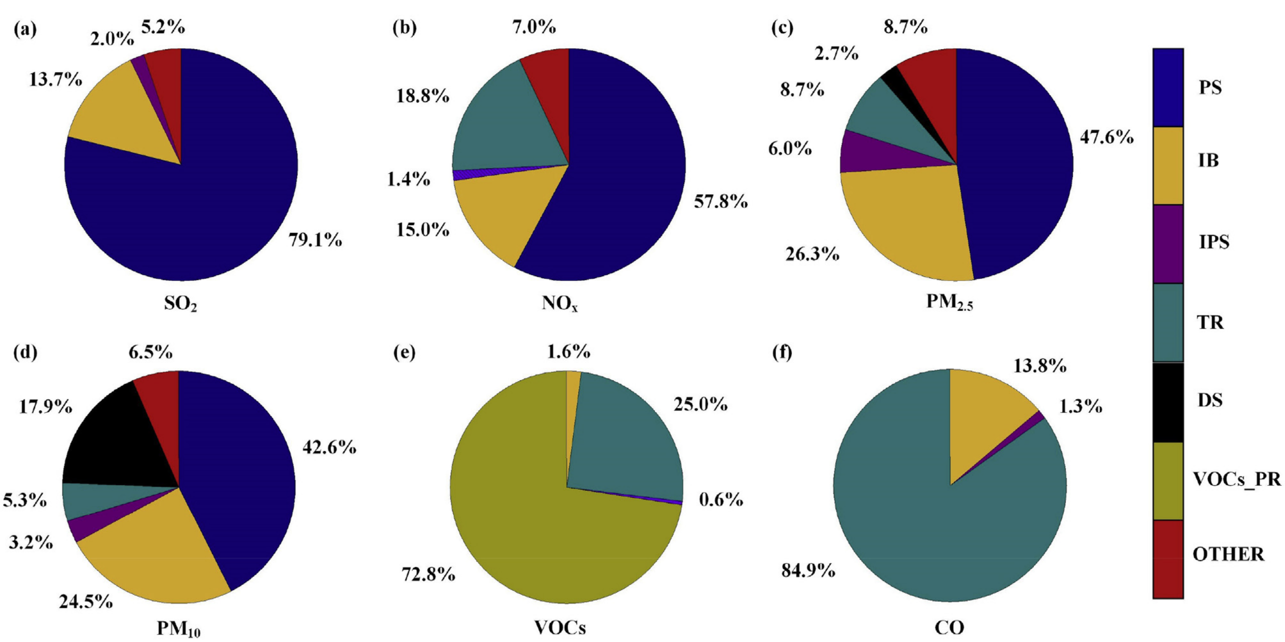

Fig. 4. The proportions of emissions reduction from various sources in total emissions reductions of air pollutants in Guangzhou between 2013 and 2016. PS: power sector, IB: industrial boiler, IPS: industrial process source, TR: transportation source, DS: dust source, VOCs_PR: VOCs product-related source, OTHER: other sources.

sets of simulation scenarios were performed. (1) Scenario 2013-BASE and scenario 2016-BASE (baseline scenario in 2013 and 2016) were designed to represent the actual air pollution situation in Guangzhou in 2013 and 2016, respectively. The simulation results from 2013-BASE and 2016-BASE were used for model verification. In addition, 2013-BASE was utilized for evaluating the air quality effects. (2) Scenario 2013-ZERO and scenario 2016-ZERO (zero emission scenario in 2013 and 2016) were designed to represent the situation that emissions of anthropogenic sources in 2013 and 2016 were shut down. (3) Scenario MET (meteorology control scenario) was designed to assess the effect of meteorology change. (4) Three regional emission control scenarios, including Guangzhou and surrounding cities emission control scenario (CTL), Guangzhou emission control scenario (GZC), and surrounding cities emission control scenario (SURC), were designed to investigate the effects of joint emissions control, local emissions control, and surrounding area emissions control by comparing with 2013-BASE. (5) Six source emission reduction scenarios, including power sector emission reduction scenario (PSC), industrial boiler emission reduction scenario (IBC), industrial process source emission reduction scenario (IPSC), transportation source emission reduction scenario (TRA), dust source emission reduction scenario (DSC), and VOCs product-related source emission reduction scenario (VOCs_PRC), were designed to evaluate the effects of emissions reduction from various sources on air pollution abatement in Guangzhou. The differences between the concentrations of air pollutants in GZC and these six scenarios were used to calculate the individual contributions of source emissions reduction. Table 1 showed the detailed description of the simulation scenarios. It should be noted that the natural emissions, initial and boundary conditions in the control scenarios (MET, CTL, GZC, SURC, PSC, IBC, IPSC, TRA, DSC, and VOCs_PRC) were identical to that in 2013-BASE and only the anthropogenic emissions or meteorological conditions were varied. Besides, the anthropogenic EIs of these simulation scenarios were generated based on the two basic PRD EIs and emissions reduction from various sources of Guangzhou.

Simulations were conducted in 4 months (January, April, July, and October) representing the winter, spring, summer, and autumn, respectively. The monthly mean concentrations of SO_2, NO_2, $PM_{2.5}$, and PM_{10} in January, April, July, and October, and the monthly 90th percentile of maximum daily 8-hr averaged O_3 concentration (Monthly 90th per MDA8 O_3, which was calculated by the method in supplementary material Section S1) in July and October were averaged to investigate the variation of air quality spatial distribution. Software for Model Attainment Test-Community Edition (SMAT-CE) developed by U.S.EPA (Wang et al., 2015) was used to adjust the simulation results with the monitor data to reduce model error. The calculation method of projecting four months average to the annual mean concentrations of SO_2, NO_2, $PM_{2.5}$, and PM_{10} was applied in this study. The ratio of 12-month average to 4-month average of monitor data in 2013 was calculated, and then the 4-month average of monitor-adjusted modeling results under different control scenario was multiplied by this ratio to represent the annual mean concentrations. O_3 is a seasonal pollutant with a higher concentration in summer and autumn. Therefore, the similar calculation method of multiplying the average of Monthly 90th per MDA8 O_3 in July and October under different control scenarios by the ratio of Annual 90th per MDA8 O_3 to 2-month (July and October) average of Monthly 90th per MDA8 O_3 in 2013 was used. The calculation equation was shown in supplementary material Section S2.

3. Results and discussion

3.1. Model performance evaluation

The meteorological observation data at Baiyun international meteorological sites (23.392°N, 113.299°E) from the National Climate Data Center (www.ncdc.noaa.gov) dataset were used to evaluate the performance of WRF model. Table S2 listed the statistical results for temperature, wind speed, and relative humidity for January, April, July, and October in 2013 and 2016. For wind speed, the average Pearson correlation coefficient (R) ranged from 0.44 to 0.76, and the Normalized Mean Bias (NMB) ranged from −23.53% to 8.77%. The correlation coefficients of temperature and relative humidity were better, ranging from 0.71 to 0.96 and from 0.80 to 0.89, respectively. Noticeably, these values were within their typical range of meteorological modeling studies (Wang et al., 2016a; Yin et al., 2017).

In this study, we conducted the air quality model evaluation using the observation data at air-monitoring sites over the PRD region from the Chinese Guangdong Environment Information Issuing Platform (http://www.gdep.gov.cn/). Fig. 5 and Fig. 6 showed overlay plot of the simulated annual mean concentrations of SO_2, NO_2, $PM_{2.5}$, and PM_{10} compared with observed concentrations for 2013 and 2016. Color circles represented the observed annual mean concentrations of SO_2, NO_2, $PM_{2.5}$, and PM_{10} at the air-monitoring sites of PRD. As shown in Figs. 5 and 6, the simulated concentration values of SO_2, NO_2, $PM_{2.5}$, and PM_{10} were consistent with the observed values in spatial pattern. Though there was a difference ranging from $-10\,\mu g\,m^{-3}$ to $10\,\mu g\,m^{-3}$ between simulated concentrations and observed concentrations in certain sites, the spatial patterns agreed well with each other, particularly in the high concentration areas.

Furthermore, the hourly model concentrations in January, April, July, and October of 2013 and 2016 were compared with observation data. The data from three typical air-monitoring sites (Huadu - a suburban site in northern Guangzhou, Sports west - an urban site in middle Guangzhou, Panyu middle school - an urban site in southern of Guangzhou) were used for the comparison with the simulation results

Table 1
Description of modeling scenarios.

Scenarios	Emissions Remarks	Meteorology	Descriptions
2013-BASE	Emissions of all sources (including anthropogenic sources, natural sources), initial and boundary conditions in 2013	Meteorology in 2013	Baseline scenario
2016-BASE	Emissions of all sources (including anthropogenic sources, natural sources), initial and boundary conditions in 2016	Meteorology in 2016	
2013-ZERO	Same as 2013-BASE except that emissions of anthropogenic sources were shut down	Meteorology in 2013	Background concentration
2016-ZERO	Same as 2016-BASE except that emissions of anthropogenic sources were shut down	Meteorology in 2016	
MET	Same as 2013-BASE	Meteorology in 2016	Effects of meteorology
CTL	Same as 2013-BASE except that emissions in Guangzhou and surrounding cities were reduced	Meteorology in 2013	Effects of air pollution control measures
GZC	Same as 2013-BASE except that only emissions in Guangzhou were reduced		
SURC	Same as 2013-BASE except that only emissions in surrounding cities were reduced		
PSC	Same as GZC except that power sector emissions reduction was removed		
IBC	Same as GZC except that industrial boiler emissions reduction was removed		
IPSC	Same as GZC except that industrial process source emissions reduction was removed		
TRA	Same as GZC except that transportation source emissions reduction was removed		
DSC	Same as GZC except that dust source emissions reduction was removed		
VOCs_PRC	Same as GZC except that VOCs product-related source emissions reduction was removed		

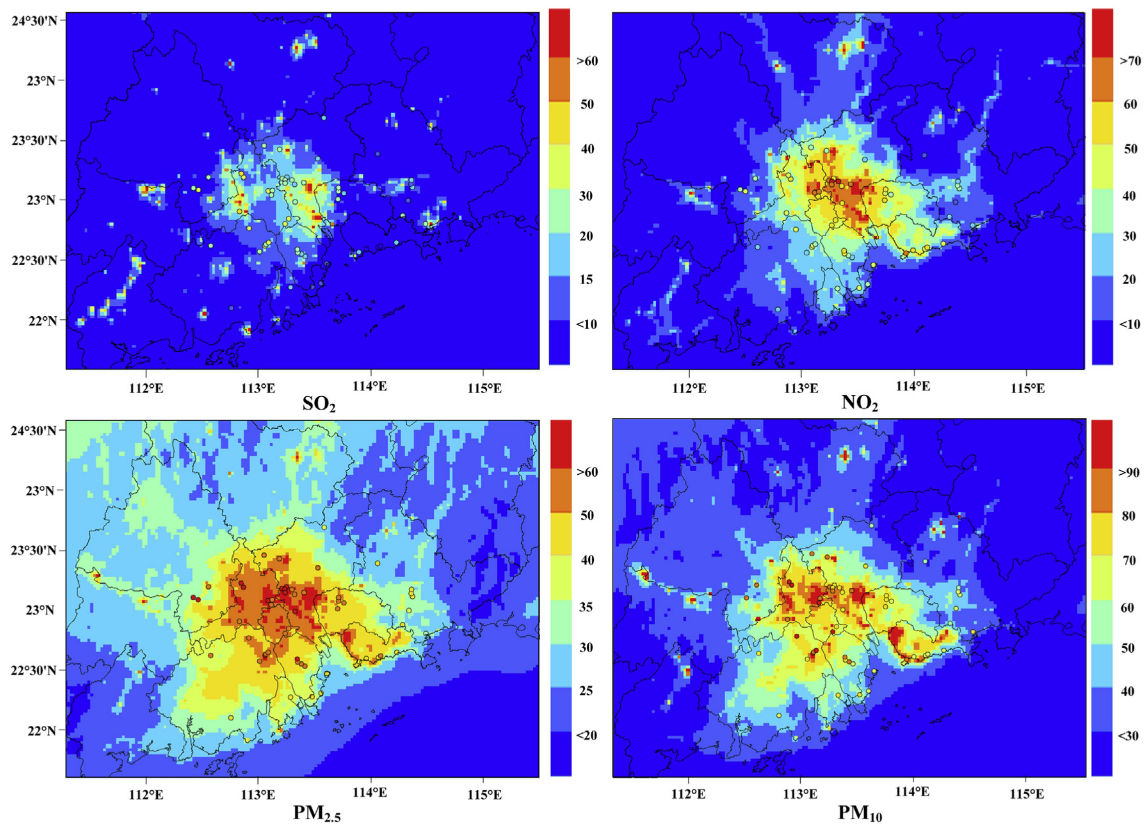

Fig. 5. Spatial distributions of simulated annual mean concentrations of air pollutants (color shaded) and observed annual mean concentrations of air pollutants (color circles) in 2013. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

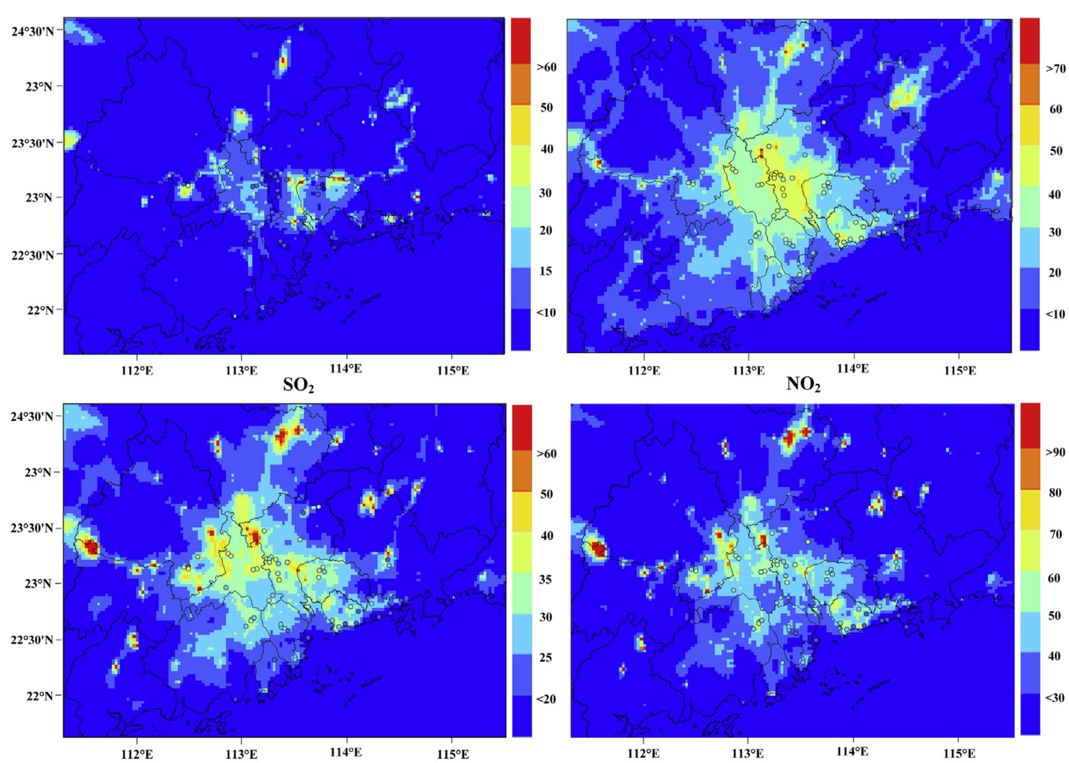

Fig. 6. Spatial distributions of simulated annual mean concentrations of air pollutants (color shaded) and observed annual mean concentrations of air pollutants (color circles) in 2016. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of the baseline scenario in 2013 and 2016. Table S3 and Table S4 summarized the statistic performance of SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3. The NMB of SO_2 was between −58.31% and 51.57%. The NMB of NO_2, $PM_{2.5}$, PM_{10}, and O_3 were lower than that of SO_2, which ranged from −30.70% to 43.56%, from −24.63% to 32.60%, from −36.14% to 23.99%, and from −35.62% to 38.62%, respectively. The Normalized Mean Error (NME) of different pollutants was 47.85%–99.03% (SO_2), 25.00%–67.58% (NO_2), 36.02%–69.80% ($PM_{2.5}$), 35.48%–60.62% (PM_{10}), and 36.00%–68.71% (O_3), respectively. The correlation coefficient of O_3, which ranged from 0.62 to 0.88, was higher than that of SO_2, NO_2, $PM_{2.5}$, and PM_{10}. According to the statistics for CTM modeling in the U.S. (U.S.EPA, 2007), the statistical values in this study were acceptable.

All the comparisons shown above suggested that the model was capable of simulating the major meteorological parameters and air pollutant concentrations, which provided a solid basis for further analysis in the following sections.

3.2. Analysis of background concentration

Background concentration is defined as the concentration in the absence of anthropogenic emissions (Asaf et al., 2008; Nopmongcol et al., 2016; Wang et al., 2019c). In this study, scenario 2013-ZERO and scenario 2016-ZERO were adopted to estimate the background concentrations of air pollutants in Guangzhou for the year 2013 and 2016. The results showed background concentrations of SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3 in 2013 at 2.6 $\mu g\,m^{-3}$, 2.5 $\mu g\,m^{-3}$, 16.6 $\mu g\,m^{-3}$, 18.0 $\mu g\,m^{-3}$, and 88.7 $\mu g\,m^{-3}$, accounting for 12.9%, 4.8%, 31.3%, 25.1%, and 56.8% of the total ambient concentrations of SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3, respectively. The contributions of background concentrations to total air pollutant concentrations in 2016 were 0.5 $\mu g\,m^{-3}$ (4.3%) for SO_2, 1.6 $\mu g\,m^{-3}$ (3.5%) for NO_2, 6.3 $\mu g\,m^{-3}$ (17.4%) for $PM_{2.5}$, 6.9 $\mu g\,m^{-3}$ (12.4%) for PM_{10}, and 87.3 $\mu g\,m^{-3}$ (56.3%) for O_3. The background concentration has a small influence on the ambient pollutant concentrations, except for O_3. The O_3 background concentrations in 2013 and 2016 made up more than half of the total ambient O_3, implying the importance of further strengthening regional joint control for O_3 pollution mitigation.

3.3. Effects of meteorological conditions

Meteorology plays an important role in air quality by affecting the advection, diffusion and deposition of air pollutants, which was mainly determined by the meteorological parameters, such as wind speed, wind direction, temperature, relative humidity, planetary boundary layer height (PBLH), precipitation, solar radiation, and cloudiness (Jones et al., 2010; Li et al., 2014; Liu et al., 2015; Mohan and Gupta, 2018; Tong et al., 2018; Xu et al., 2016). As shown in Table 1, scenario MET was simulated to evaluate the effects of meteorology conditions on air quality in Guangzhou. Compared to scenario 2013-BASE, the concentrations of SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3 of scenario MET decreased by 3.1 $\mu g\,m^{-3}$ (15.5%), 2.4 $\mu g\,m^{-3}$ (4.6%), 6.9 $\mu g\,m^{-3}$ (13.1%), 9.3 $\mu g\,m^{-3}$ (12.9%), and 3.5 $\mu g\,m^{-3}$ (2.2%). It meant that the meteorology in 2016 was favorable for air quality improvement compared to that in 2013.

Focus on the meteorological parameters, although PBLH decreased by 8.3 m in 2016 compared to 2013 (Table 2), the average wind speed and total precipitation in 2016 were 0.1 $m\,s^{-1}$ and 582.1 mm larger than that in 2013, and this could alleviate the concentrations of air pollutants. The higher temperature was also favorable to the vertical dilution and diffusion of air pollutants (Huang et al., 2017). What's more, relative humidity, cloud cover, and solar radiation are the essential factors for O_3 chemical reaction (Katragkou et al., 2011; Pu et al., 2017). Pu et al. (2017) found that lower relative humidity, less cloud cover, and more net solar radiation are beneficial to the photochemical reaction and result in more production of O_3. The relative humidity increased by 4.5% in 2016 compared with that in 2013, cloud fraction increased by 5.4% and net solar radiation decreased by 11.1 w m^2, which resulted in less O_3 in 2016 and more O_3 in 2013.

Table 2
Meteorology conditions in 2013 and 2016.

Year	T (°C)	RH (%)	TP (mm)	WS ($m\,s^{-1}$)	PBLH (m)	CF (%)	SR ($w\,m^2$)
2013	22.0	76.8	2056.0	2.5	528.2	57.4	169.2
2016	22.4	81.3	2638.1	2.6	519.9	62.8	158.1

Note: T-temperature, RH-relative humidity, TP-total precipitation, WS-wind speed, PBLH-planetary boundary layer height, CF-cloud fraction, SR-solar radiation. Temperature, relative humidity, and wind speed represented the annual mean values in 2013 and 2016, precipitation represented total rainfall in 2013 and 2016, which were available from Guangzhou Statistical Yearbook (GZSB, 2014; 2017). The annual average values of PBLH, cloud fraction, and solar radiation were derived from WRF model simulations.

3.4. Effects of air pollution control measures implemented in Guangzhou and surrounding cities

Fig. 7 showed the spatial distributions of changes in air pollutant concentrations due to emission control measures implemented in Guangzhou and surrounding cities. In the Guangzhou region, the concentrations of SO_2 and NO_2 dropped significantly in most areas except individual grids where industrial point source located. The concentrations of $PM_{2.5}$ and PM_{10} also displayed an obvious decrease, though there were increases in a few grids distributed construction emission sites. For O_3, there were some slightly increasing grids in the southern Guangzhou. The quantitative effects of emission control measures on the concentrations of air pollutants in Guangzhou were shown in Fig. 8. After the implementation of emission control measures in both Guangzhou and surrounding cities, the concentrations of SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3 were decreased by 9.7 $\mu g\,m^{-3}$ (48.4%), 9.2 $\mu g\,m^{-3}$ (17.7%), 7.7 $\mu g\,m^{-3}$ (14.6%), 9.7 $\mu g\,m^{-3}$ (13.4%), and 12.0 $\mu g\,m^{-3}$ (7.7%), respectively. If the control measures were only implemented in Guangzhou, the concentrations of SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3 decrease by 9.2 $\mu g\,m^{-3}$ (46.0%), 7.9 $\mu g\,m^{-3}$ (15.2%), 5.0 $\mu g\,m^{-3}$ (9.4%), 6.6 $\mu g\,m^{-3}$ (9.1%), and −3.7 $\mu g\,m^{-3}$ (−2.4%), respectively. Only implementing control measures in surrounding cities could have led to 0.8 $\mu g\,m^{-3}$ (3.8%), 1.6 $\mu g\,m^{-3}$ (3.0%), 2.8 $\mu g\,m^{-3}$ (5.4%), 3.7 $\mu g\,m^{-3}$ (5.2%), and 15.3 $\mu g\,m^{-3}$ (9.8%) decrease in SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3, respectively.

The results indicated that the joint emissions control from Guangzhou and surrounding cities was most effective to improve the air quality of Guangzhou, implying that the joint control measures should be strengthened in the future. What's more, compared with surrounding area emissions control, local emissions control was more helpful in the reduction of the concentrations of SO_2, NO_2, $PM_{2.5}$, and PM_{10}. As for O_3, the effect of local emissions control was negative while the surrounding area emissions control was positive. The unexpected rise of O_3 concentration in response to local emissions control was due to the weakening titration effects of NO to O_3 ($NO + O_3 = NO_2 + O_2$) (Lin et al., 2005; Liu et al., 2013; Wang et al., 2016a). It indicated that an appropriate control ratio between NO_x and VOCs is important for the O_3 pollution mitigation in Guangzhou.

3.5. Effects of emissions reduction from various sources in Guangzhou

Fig. 9 showed the spatial distributions of changes in air pollutant concentrations due to emissions reduction from various sources in Guangzhou. The differences in the concentrations of SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3 from power sector emissions reduction were higher than

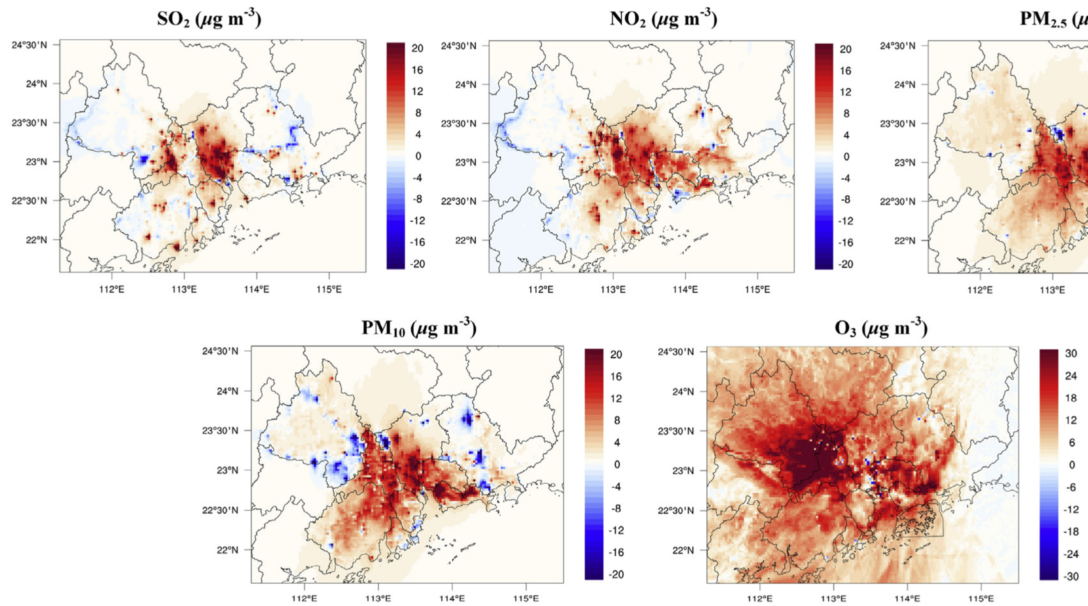

Fig. 7. Changes in the concentrations of SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3 due to the emission control measures in Guangzhou and surrounding cities (2013-BASE - CTL).

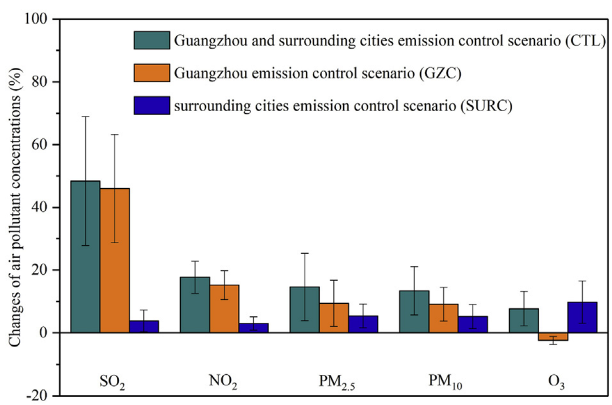

Fig. 8. The reduction of the concentrations of SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3 under three regional emission control scenarios (CTL, GZC, and SURC) compared with baseline scenario in 2013 (2013-BASE). The error bars indicated one standard deviation.

that from other sources emissions reduction. Fig. 10 presented the individual contributions of source emissions reduction in reducing air pollutant concentrations. Power sector emissions reduction, industrial boiler emissions reduction, and industrial process source emissions reduction decreased SO_2 concentration by 6.0 $\mu g\,m^{-3}$, 1.0 $\mu g\,m^{-3}$, and 0.9 $\mu g\,m^{-3}$, respectively. The magnitude of the reduction in NO_2 concentration from power sector emissions reduction, industrial boiler emissions reduction, industrial process source emissions reduction, and transportation source emissions reduction was 2.9 $\mu g\,m^{-3}$, 0.5 $\mu g\,m^{-3}$, 0.5 $\mu g\,m^{-3}$, and 0.7 $\mu g\,m^{-3}$, respectively. The reductions of power sector, industrial boiler, industrial process source, transportation source, dust source, and VOCs product-related source decreased $PM_{2.5}$ concentration by 1.5 $\mu g\,m^{-3}$, 0.8 $\mu g\,m^{-3}$, 0.7 $\mu g\,m^{-3}$, 0.6 $\mu g\,m^{-3}$, 0.3 $\mu g\,m^{-3}$, and 0.1 $\mu g\,m^{-3}$, and they decreased PM_{10} concentration by 2.1 $\mu g\,m^{-3}$, 1.2 $\mu g\,m^{-3}$, 0.7 $\mu g\,m^{-3}$, 0.6 $\mu g\,m^{-3}$, 1.0 $\mu g\,m^{-3}$, and 0.1 $\mu g\,m^{-3}$.

It can be found that the emissions reduction of power sector contributed the largest to the reduction of the concentrations of SO_2, NO_2, $PM_{2.5}$, and PM_{10} as the Ultra-Clean control technology were put into effect. Industrial boiler was the second biggest contributor to lowering the concentrations of SO_2, $PM_{2.5}$, and PM_{10} and the third biggest contributor to reducing NO_2 concentration. It indicated that eliminating high-polluted fuel boilers was effective to improve air quality. Although industrial process source was the last or the penultimate contributor to the total emissions reductions of SO_2, NO_2, $PM_{2.5}$, and PM_{10} (Fig. 4), it had the third largest contribution in reducing the concentrations of SO_2 and $PM_{2.5}$ and the fourth largest contribution in reducing the concentrations of NO_2 and PM_{10}. This was because the 19 heavily polluting industrial enterprises, which shut down between 2014 and 2016, were just near the air-monitoring sites. Therefore, industrial process source still possessed the reduction potential. The emission reduction contributions of transportation source in reducing the concentrations of NO_2, $PM_{2.5}$, and PM_{10} were lower than that of power sector, although measures have been taken to eliminate yellow-labeled vehicles and old vehicles and update the emission standards of petrol/diesel in Guangzhou. Possible reasons were the continuously growing of local vehicle population and entering of non-local vehicles during the period of 2013 and 2016. It indicated that controlling transportation source emission had the potential to reduce the concentrations of NO_2, $PM_{2.5}$, and PM_{10}, hence, it is recommended to restrict the entry number of non-local vehicle and promote the use of electric bus on the next step. Additionally, dust source has become one of the dominant contributors to the emissions of $PM_{2.5}$ and PM_{10} in the PRD region (Yin et al., 2017; Zhong et al., 2018), but the emission reduction contributions of dust source to the reduction of the concentrations of $PM_{2.5}$ and PM_{10} were lower than that of power sector. The results suggested that there was reduction potential in dust source, so more strict control measures for dust source need to be performed.

For O_3 pollution mitigation, VOCs product-related source was the most important contributor, followed by transportation source. In contrast, the reductions of power sector, industrial boiler, and industrial process source were found to increase O_3 concentration, because the NO_x emissions reduction of above sectors was significantly higher than VOCs emissions reduction, especially for power sector. The titration effects of NO to O_3 will be restrained when reducing local NO_x emissions (Dong et al., 2013; Han et al., 2018). The side effect of NO_x reduction to O_3 totally overshadowing the effect of VOCs reduction caused the slightly increased ambient O_3 in Guangzhou. However, the power plant emissions reduction had a positive contribution to abating the O_3 in the downwind cites (Fig. 9a). Therefore, more VOCs control measures should be adopted when implementing NO_x control measures

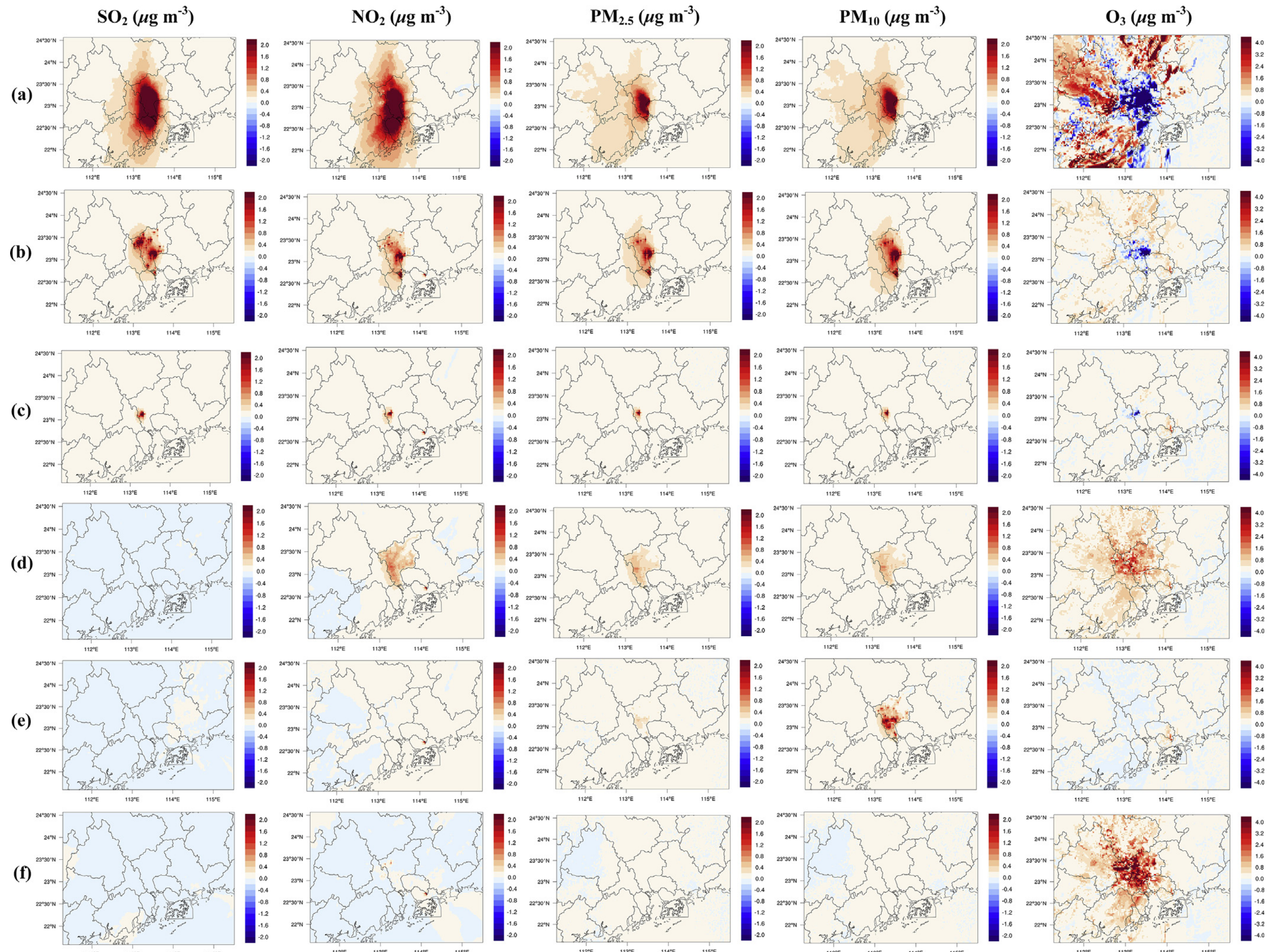

Fig. 9. Changes in the concentrations of SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3 due to: (a) power sector emissions reduction (PSC - GZC), (b) industrial boiler emissions reduction (IBC - GZC), (c) industrial process source emissions reduction (IPSC - GZC), (d) transportation source emissions reduction (TRA - GZC), (e) dust source emissions reduction (DSC - GZC), (f) VOCs product-related source emissions reduction (VOCs_PRC - GZC).

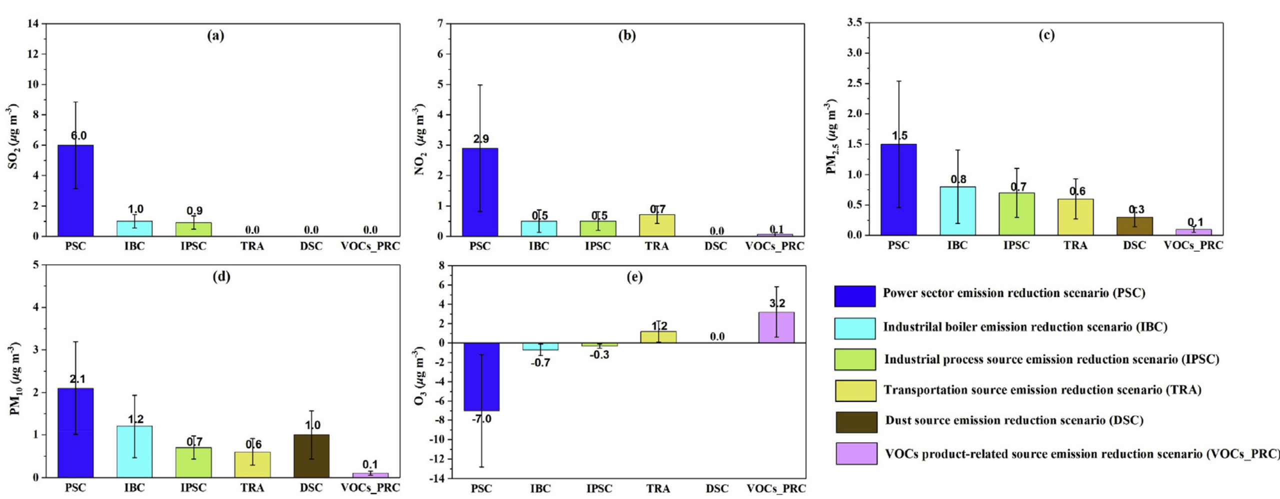

Fig. 10. The reduction of the concentrations of (a) SO_2, (b) NO_2, (c) $PM_{2.5}$, (d) PM_{10}, and (e) O_3 by comparing Guangzhou emission control scenario (GZC) with six simulation scenarios (PSC, IBC, IPSC, TRA, DSC, and VOCs_PRC). The error bars indicated one standard deviation.

to alleviate O_3 pollution in Guangzhou. Actually, transportation source had reduction potential not only in the emissions of NO_2, $PM_{2.5}$, and PM_{10} but also in VOCs emissions. Furthermore, industrial solvent usage source and industrial process source still had a large potential to control VOCs emissions because of the lower efficiency of presently implemented VOCs treatment technology (Zhong et al., 2018). Integrated control on petroleum and chemical industry, shipbuilding and container, and other industrial painting industry will effectively reduce VOCs emissions (GDEEP, 2018).

4. Conclusion

Taking 2013 as the base year, we investigated the relative effects of meteorology change, joint emissions control, local emissions control, and surrounding area emissions control on air quality improvement in Guangzhou after the implementation of pollution control measures from 2014 to 2016. Furthermore, we quantitatively assessed the contributions of emissions reduction from various sources in Guangzhou to air pollution abatement.

This study showed that favorable meteorological conditions, such as larger wind speed and more precipitation in 2016, alleviated the air pollution in Guangzhou, which resulted in $3.1\,\mu g\,m^{-3}$ (15.5%), $2.4\,\mu g\,m^{-3}$ (4.6%), $6.9\,\mu g\,m^{-3}$ (13.1%), $9.3\,\mu g\,m^{-3}$ (12.9%), and $3.5\,\mu g\,m^{-3}$ (2.2%) decrease for SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3, respectively. Compared to change in meteorology, joint emissions control from Guangzhou and surrounding cities was more beneficial for the improvement of air quality, and it could reduce SO_2, NO_2, $PM_{2.5}$, PM_{10}, and O_3 by $9.7\,\mu g\,m^{-3}$ (48.4%), $9.2\,\mu g\,m^{-3}$ (17.7%), $7.7\,\mu g\,m^{-3}$ (14.6%), $9.7\,\mu g\,m^{-3}$ (13.4%), and $12.0\,\mu g\,m^{-3}$ (7.7%). In addition, we found that the local emissions control in Guangzhou contributed more to the reduction of the concentrations of SO_2, NO_2, $PM_{2.5}$, and PM_{10} in comparison to surrounding area emissions control, but it slightly increased O_3 concentration.

In terms of the individual contributions of local source emissions reduction, results showed that industrial point sources (including power sector, industrial boiler, and industrial process source) were the important contributors to the reduction of the concentrations of SO_2, NO_2, $PM_{2.5}$, and PM_{10}. Moreover, power sector emissions reduction made the largest contribution, which has significant effects on improving air quality. Despite the efforts on emissions reduction, transportation source had a lower contribution to the reduction of the concentrations of NO_2, $PM_{2.5}$, and PM_{10} compared to power sector. The emission reduction contributions of dust source in reducing the concentrations of $PM_{2.5}$ and PM_{10} were lower than that of power sector. VOCs product-related source and transportation source were the two top contributors to the reduction of O_3 concentration, while the reductions of industrial point sources were counterproductive.

Based on the analysis results of this study, there were two recommendations for further air quality improvement in Guangzhou: (1) more regional joint control measures and actions are necessary in Guangzhou and surrounding cities; (2) for local emission control, more sound control measures for industrial process source and transportation source should be adopted to reduce NO_2 concentration. As for $PM_{2.5}$ and PM_{10}, continuous tightening controls on industrial process source, transportation source, and dust source will lead to a significant reduction. Moreover, it is necessary to reinforce the control measures on industrial solvent usage source, industrial process source, and transportation source to reduce VOCs emissions when implementing NO_x control measures, which will be beneficial for the mitigation of O_3 pollution.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.05.046.

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