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An integrated modelling framework for evaluating the synergistic impacts of low-carbon transitions and air pollution controls on air quality and health in Guangzhou, China

Yun SHU[a], Yang LI[a], Yazhen WU[b], Xiang-Zhao FENG[c], Sha-Sha XU[d], Ya-Li WANG[a], Tong MA[a], Jian-Hua CHEN[a], Jian GAO[a,*], Shaohui ZHANG[b], Ji-Zhang HUANG[e]

[a] State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China

[b] International Institute for Applied Systems Analysis, Laxenburg 2361, Austria

[c] China Center for Information Industry Development, Beijing 100048, China

[d] Yellow River Research Institute, North China University of Water Resources and Electric Power, Zhengzhou 450046, China

[e] Guangzhou Research Institute of Environment Protection Company Limited, Guangzhou 510665, China

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Abstract

Climate policies that target carbon emissions can induce co-benefits for air quality. Previous urban studies have typically focused on either carbon reduction or air pollution control independently, but few have examined their combined effects on reducing carbon emissions and consequential environmental gains. We develop an integrated modelling framework to assess the impacts of different low-carbon transitions and end-of-pipe controls on $PM_{2.5}$ and ozone concentrations and associated premature mortality in the megacity of Guangzhou. The results show that the implementation of both deep carbon mitigation and aggressive air pollution control policies can reduce the city's pollutant emissions to 34%−51% of the 2020 levels by 2035. Consequently, the population-weighted $PM_{2.5}$ concentration in 2035 is projected to decrease by 5 $\mu g/m^3$ compared to the 2035 baseline scenario. However, the ozone concentration is expected to rise by 35 $\mu g/m^3$ due to the reduced titration effect of NO on ozone. These changes are estimated to prevent approximately 3.0 thousand (95% CI: 2.0−3.9) $PM_{2.5}$-related premature deaths, while increasing ozone-related premature deaths by approximately 1.6 thousand (95% CI: 0.7−2.7). Moreover, implementing multiregional integrated control measures in Guangzhou and its neighbouring cities yields greater air quality and health benefits for Guangzhou compared to local enforcement alone, resulting in 1.5 times more avoided $PM_{2.5}$-related premature deaths. Additionally, the increase in ozone-related premature deaths from these cooperative emission control strategies is merely 0.3 times the figure observed under local enforcement alone. The transport and industry sectors play a crucial role in reducing air pollutant emissions, whereas reductions in the solvent use sector can help mitigate the adverse effects of reduced NO_x on ozone pollution. These findings highlight the need for comprehensively multiregional strategies to balance the trade-offs between reducing $PM_{2.5}$ and ozone-related health impacts, offering valuable insights for urban policy makers aiming to optimize both climate and air quality goals on a broader scale.

Keywords: Low-carbon pathways; Air pollution control; Health impact; Megacities

1. Introduction

Cities play a central role in both climate change mitigation and air pollution control efforts. On the one side, cities are the primary hubs of energy use and greenhouse gas (GHG) emissions, accounting for 75% of carbon dioxide (CO_2) from

* Corresponding author.

E-mail address: gaojian@craes.org.cn (GAO J.).

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energy use around the world (IEA, 2019). On the other side, nearly 99% of urban areas in developing countries fail to meet the World Health Organization's air quality guideline of 5 μg/m^3, with pollution contributing to millions of premature deaths each year (WHO, 2023). Taking China as an example, CO_2 emissions from Chinese cities have increased threefold between 2020 and 2020. In 2019, these cities emitted 8486 Mt CO_2 (direct emissions within city boundaries). Moreover, approximately 1.4 million people died prematurely because of urban fine particulate matter ($PM_{2.5}$) exposure in China, and an additional 93,271 (95% confidence interval (CI): 42,665−151,062) deaths were attributable to surface ozone exposure (Lu et al., 2020; Murray et al., 2020). Therefore, cities must address climate change and air pollution simultaneously, both within and beyond their boundaries.

The literature has noted that mitigation policies aimed at CO_2 reduction can also have substantial co-benefits for air pollution and associated health impacts. This has been thoroughly quantified at both global and national scales. For instance, a global study estimated that the GHG abatement scenario (the representative concentration pathway 4.5) could prevent 0.4 ± 0.2 million $PM_{2.5}$ and 0.09 ± 0.06 million ozone-related premature deaths worldwide by 2030, with two-thirds of these benefits occurring in China (West et al., 2013). In China, Tang et al. (2022) highlighted the role of environmental policies (end-of-pipe controls) in reducing the public health burden.

Given the significant regional heterogeneity in China, the synergy pathways between CO_2 emission reduction and air pollution control policies can vary greatly across cities. Therefore, city-specific research is essential to develop tailored strategies for reducing local CO_2 emissions and air pollutants, enabling Chinese cities to achieve multiple environmental targets effectively. For example, Ramaswami et al. (2017) studied the effects of CO_2 reduction strategies in 637 cities in China and reported considerable heterogeneity in health co-benefits for $PM_{2.5}$, ranging from 1% to 47% for avoided premature deaths. Jiang et al. (2021) reported that climate governance of Shenzhen would synergistically contribute to decreasing urban annual $PM_{2.5}$ concentration by almost 6% in 2030. Wu et al. (2021) examined the effects of peak carbon emissions on air quality and public health in Guangzhou and reported that energy transition policies involving clean energy substitution, industrial structure optimization and energy saving technology could prevent approximately 1460 $PM_{2.5}$-attributable deaths in 2030. Lu et al. (2022) assessed the health co-benefits of transitioning to low-carbon transport in Beijing and reported that decarbonizing urban passenger transport could prevent 300 (95% CI: 229−450) premature deaths annually attributable to $PM_{2.5}$ exposure.

In general, previous city-level studies have largely focused on the impacts of climate and air pollution policies independently, with limited attention to their combined effects on air quality and associated health outcomes. Moreover, while many studies have assessed the benefits of local air quality improvements from emission controls, few have evaluated the effects of multiregional integrated control strategies. In fact, urban air quality, particularly ozone pollution, is heavily affected by atmospheric transport from nearby regions (Lelieveld et al., 2015; Li et al., 2019a,b). To address this gap, we develop an integrated assessment framework that incorporates climate, air quality and human health considerations. This framework evaluates the effectiveness of various low-carbon policies and air pollution control strategies in mitigating the health impacts of both $PM_{2.5}$ and ozone pollution at the city-level, while clarifying the critical roles of multiregional synergic control. Importantly, this approach helps balance the trade-offs between reducing $PM_{2.5}$-related health impacts and managing the increased ozone-related health risks associated with NO_x reductions in urban areas (NO_x-saturated regime) (Li et al., 2019b; Lu et al., 2018).

As the capital of Guangdong province and a megacity in the Pearl River Delta (PRD), Guangzhou faces the combined challenges of carbon emissions and air pollution. The city's direct carbon emissions have increased steadily since 2010, and it continues to experience poor air quality, particularly that related to ozone pollution. In 2012, the National Development and Reform Commission designated Guangzhou as a national low-carbon pilot city (TPGGM, 2017). Subsequently, multiple air pollution control measures have been carried out to control city's $PM_{2.5}$ and ozone in combination (DEEGP, 2018). Thus, Guangzhou's exploration of CO_2 emissions and air pollution synergistic governance provides a reference for other megacities in developing countries.

This study expands the existing body of knowledge by providing a detailed assessment of the combined effects of low-carbon transitions and aggressive air pollution controls on both $PM_{2.5}$ and ozone concentrations in the urban setting of Guangzhou, which have not been fully quantified at a city-level scale in past studies (Jiang et al., 2021; Lu et al., 2022; Ramaswami et al., 2017; Wu et al., 2021). We also simulate the impact of a cross-city cooperative control strategy on Guangzhou by comparing an urban local emission control scenario with a regional synergic governance scenario. The contributions of this study are as follows: First, we present an interdisciplinary framework that integrates energy, emission, air quality, and health risk assessment models at the city scale. This approach provides a comprehensive and quantitative assessment of the synergistic effects of low-carbon transitions and air pollution controls, while promoting sustainable urban development and improved public health. Second, we provide new insights into the trade-offs between $PM_{2.5}$ reductions and ozone increases arising from the implementation of energy and environmental policies at the city level.

2. Method

The long-range energy alternative planning (LEAP) model, the greenhouse gas and air pollution interactions and synergies (GAINS) model, the comprehensive air quality model with extensions (CAMx) model, and exposure−response functions (ERFs) were coupled to capture the nonlinearities among energy, emissions, concentrations and health, thus allowing us to assess the quantitative effects of carbon mitigation and air pollution control policies in Guangzhou city. Fig. 1 illustrates the overall modelling framework. We first developed a city-level LEAP model to estimate energy consumption and energy-related CO_2 emissions under two different energy transition scenarios. Sectoral energy use given by the LEAP model were then used as the activity pathway input for the GAINS model. Combining this activity estimation with different air pollution control strategies, GAINS was used to calculate emissions of $PM_{2.5}$, SO_2, NO_x and VOCs and the costs of air pollution control. On the basis of the resulting air pollutant emissions, the CAMx model output ambient air quality (annual $PM_{2.5}$ and ozone concentrations) in Guangzhou. Finally, the global exposure mortality model (GEMM) was used to estimate the number of premature deaths related to $PM_{2.5}$ and ozone pollution.

2.1. LEAP model

The LEAP model is an integrated tool for simulating energy production, consumption, and GHG emissions (SEI, 2006). To study the potential for urban energy conservation and CO_2 reduction, a customized LEAP-Guangzhou model was developed. LEAP-Guangzhou consists of two modules—the final energy demand module and the energy transformation module (Fig. A1)—which encompass primary and secondary energy sources utilized in urban areas. Based on the characteristics of energy use in Guangzhou, demand modules are branched into six end-use sectors: transport, industry, construction, household, commerce and agriculture. Every sector comprises relevant subsectors, equipment, and fuel types on the basis of the specific characteristics of energy demand within that sector. For example, the transportation sector is subdivided into eight subsectors: motorcycles, light-duty and heavy-duty vehicles, construction machines, agricultural machines, rail transit, air transport, and water transport. Additionally, the energy transformation module consists of three sectors: electricity and heat supply, transmission and distribution, and oil refining. Electricity and heat supply sector includes coal, liquefied natural gas, and renewable sources such as solar power, hydropower, and wind power. Detailed

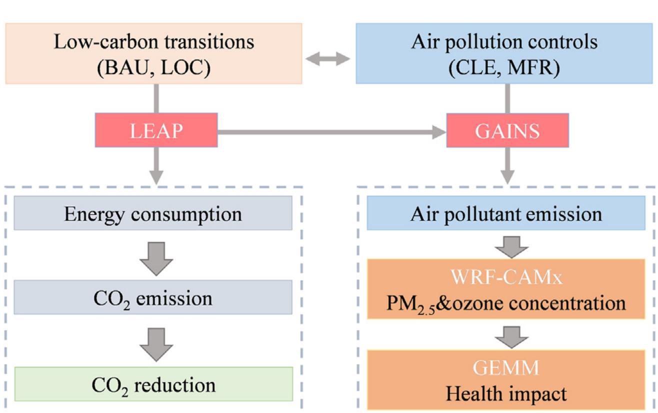

Fig. 1. Integrated modelling framework.

information about the LEAP-Guangzhou model is provided in Text A1. The model covers the period from 2020 to 2035, with 2020 as the baseline year and a five-year interval between assessments.

According to our LEAP-Guangzhou model estimates, for 2020, Guangzhou's total energy consumption, including energy consumption from end-use sectors and energy transformation, was approximately 61.5 Mtce, of which the share of oil accounted for 35.2%, electricity accounted for 31.6%, and coal accounted for only 12.7% (Fig. A2). Our estimate of the energy usage pattern agrees well with the statistical yearbook (GSB, 2021). On the basis of energy consumption in Guangzhou, CO_2 emissions (direct emissions within city boundaries without considering purchased electricity emissions) in 2020 totalled 93 Mt. The deviation between our results and the official inventory for CO_2 emissions is less than 2% (Fig. A3). The results from Wu et al. (2021) considered emissions from heat and electricity produced outside Guangzhou and thus are higher than our estimates.

2.2. GAINS model

We applied the GAINS-China model and focused on Guangzhou to analyse the effects of CO_2 reduction measures and end-of-pipe control technologies on air pollutant emissions. Forecasts of future economic and energy activity, obtained from the LEAP-Guangzhou model, were input into the GAINS model as the activity pathway. This activity estimation was combined with emission factors and control strategy data (end-of-pipe technology mix) to simulate implementation of air quality legislations. Before the LEAP and GAINS models were coupled, current emissions were estimated based on Guangzhou statistics and emission inventories by modifying the built-in energy activity data and control strategies for 2020 in the GAINS model (see details in Text A2).

As presented in Fig. A3, our air pollutant emission estimates are quite close to those of the Guangzhou emission inventories for 2020, with relative errors within 2%. However, the estimations by Wu et al. (2021) and Yu et al. (2019) indicate that air pollutant levels are 6%−57% higher than ours. This is because their results were based on emission projections from 2015, which underestimated the effectiveness of environmental legislation from 2015 to 2020.

LEAP and GAINS differ in terms of sector definitions and fuel-type classifications; therefore, mapping matrices for activity variables were developed to facilitate the coupling of the two models (Text A3 and Table A1). GAINS estimates emission control costs on the basis of the add-on abatement technologies/measures applied in each policy, excluding the costs associated with changes in the fuel mix and energy consumption (Amann et al., 2011). Therefore, air pollutant emission abatement costs were extracted from the GAINS-China model to analyse the reduction in pollution control expenses under the low-carbon transition scenario. The costs reported in this work are adjusted to constant prices (2005 EUR).

2.3. Air quality model

We used the Weather Research and Forecasting (WRF v3.7.1) model and the Comprehensive Air Quality Model with Extensions (CAMx v6.4) to simulate the concentrations of $PM_{2.5}$ and ozone for 2020 and future scenarios in 2035. Domain 1 covered mainland China and parts of Asia with a grid resolution of 36 km × 36 km. Domain 2, with a grid resolution of 12 km × 12 km, included parts of central and southern China. The innermost domain 3 targeted Guangzhou city and its surrounding cities at a 4 km × 4 km resolution (Fig. A4). The carbon bond 6 mechanism and the static two-mode coarse/fine scheme were applied for gas-phase chemistry and particle size distribution, respectively. Meteorological conditions from the National Center for Environmental Prediction Final Analysis reanalysis data were applied to drive the WRF model. In line with previous studies (Chen et al., 2019; Jiang et al., 2021), WRF simulations for January, April, July and October—based on the meteorological characteristics of Guangzhou, were selected as the meteorological input for the CAMx simulations.

Baseline 2020 emissions and three 2035 policy scenario emissions defined in Table 1 were used for Guangzhou city in the innermost layer (domain 3). Emissions outside Guangzhou were taken from the 2020 Multiresolution Emission Inventory (MEIC model tracking anthropogenic emissions). Besides anthropogenic emissions, emissions from other sources are required by CAMx. In this case, biogenic emissions were taken from the Model of Emissions of Gases and Aerosols from Nature version 2.1 (Guenther et al., 2012), which were driven by real-time meteorological conditions provided by our WRF simulations. Sea-salt and windblown dust emissions were obtained via the CAMx model online. These emissions were processed into the model-ready format via the Sparse Matrix Operator Kernel Emissions model. To maintain consistency and focus on anthropogenic emissions and policy impacts, biogenic emissions were assumed to remain constant, calculated using the same meteorological conditions as the 2020 baseline. To eliminate the impact of meteorological conditions on air pollutant concentration, the same meteorological field as that in the 2020 baseline was used for all future scenarios. The statistical results for temperature, wind speed and relative humidity indicate that the WRF model provides acceptable performance in simulating meteorological parameters for further air quality simulations (Table A2). The model's performance in replicating $PM_{2.5}$ and ozone concentrations was assessed by comparing the 2020 simulated results with observational data from 21 air quality monitoring stations throughout the city (Table A3). Overall, the simulated annual mean $PM_{2.5}$ and maximum daily 8-h average (MDA8) ozone concentrations correlated well with the observations in Guangzhou city, with mean biases of 0.11 and −22.2 $\mu g/m^3$, normalized mean biases of 0.5% and −21.8%, and IOA values of approximately 0.8 or greater (Fig. A5).

Table 1
Scenario definitions.

Scenario	Low-carbon energy policies	Air pollution control policies
BAU-CLE	Existing carbon mitigation policies	End-of-pipe control measures under stated air quality policies and targets
BAU-MFR	Same as energy scenario in BAU-CLE	Aggressive end-of-pipe controls to achieve maximum feasible emission reduction
LOC-MFR	Additional low-carbon energy policies beyond the BAU	Same as pollution control scenario in BAU-MFR

2.4. Health impact assessment

The health impacts of long-term $PM_{2.5}$ exposure on ischaemic heart disease (IHD), stroke (STK), lung cancer (LC), chronic obstructive pulmonary disease (COPD), and lower respiratory infections (LRIs) were assessed, as were the health impact of long-term ozone exposure on cardiovascular (CVD) and respiratory (RESP) diseases. The number of premature deaths attributable to air pollution can be calculated via the relative risk (R_{R}) model method as follows:

$$\Delta Y = A \times Y \times P$$

where $\triangle Y$ is disease-specific mortality impacts associated with long-term annual $PM_{2.5}$ or ozone (maximum daily 8-h average, MDA8) exposure; $A = 1 - 1/R_{\mathrm{R}}$ represents the population attributable fraction, where R_R stands for the relative risk for a specific disease; Y is the baseline disease-specific mortality rate (this study used the results from the Global Burden of Disease project (Institute for Health Metrics and Evaluation) to estimate Y, which were assumed to remain unchanged until 2035); and P represents the age-specific population that is exposed in each grid in Guangzhou. It was assumed that the spatial distribution of the population and baseline mortality rates would remain constant from 2020 to 2035.

To estimate the R_{R} due to $PM_{2.5}$ exposure, we used the GEMM 5-COD (IHD, STK, LC, COPD and LRI), which was developed on the basis of cohort studies across 16 countries, including a recent study conducted in China (Burnett et al., 2018). The R_{R} function utilized by the GEMM is as follows:

$$R_{\mathrm{R}} = \mathrm{e}^{\left\{\frac{\theta \times \log\left(\frac{C-2.4}{\alpha}+1\right)}{1+\mathrm{e}^{\left(-\frac{C-2.4-\mu}{\nu}\right)}}\right\}}$$

where C is the ambient $PM_{2.5}$ exposure for each grid; θ, α, μ and ν are the GEMM parameters from Burnett et al. (2018); R_{R} of IHD and R_R of STK are calculated by age, and all-age R_{R} are calculated for the other three endpoints. The 95% confidence intervals (CIs) of premature deaths are derived from the standard error θ (Burnett et al., 2018).

To estimate the health impacts of ambient ozone exposure, we applied a log-linear function to calculate mortality:

$R_R = e^{\beta(C-C_0)}$

where C is the ambient MDA8 ozone exposure for each grid; C_0 denotes the threshold concentration of 70 μg/m^3, no additional risk is assumed below this level (Lelieveld et al., 2015); β is the change of mortality per ozone increase, which can be derived from the RR for a 20 μg/m^3 increase in the annual average MDA8 ozone. For RESP, the R_R is 1.12 (95% CI: 1.08−1.16), while for CVD, it is 1.03 (95% CI: 1.01−1.05) (Turner et al., 2016). Adults aged 30 years and older are selected for mortality estimations according to Turner et al. (2016).

In addition, to test the uncertainty in mortality estimated by different ERFs functions, we calculated $PM_{2.5}$-attributable premature death based on the integrated exposure response (IER) for five endpoints (IHD, STK, LC, COPD and LRI) (Stanaway et al., 2018) and log-linear functions for all-cause mortality (Pope et al., 2002). We also calculated ozone-attributable premature death from older estimates, which had R_R of 1.04 (95% CI: 1.013−1067) for RESP (Jerrett et al., 2009) and 1.01 (95% CI: 1.00−1.02) for CVD (Atkinson et al., 2016). Details on the descriptions of mortality adopted by other models are discussed in Text A4.

2.5. Scenario setting

As shown in Table 1, the scenarios were established across two dimensions. One dimension considers the CO_2 reduction measures, where scenarios labelled BAU assume the implementation of existing energy policies and are extrapolated beyond 2020. Scenarios labelled LOC assume the implementation of low-carbon energy policies beyond the BAU; these include industrial and transport structure adjustments, clean energy substitution, energy efficiency improvements, and the utilization of renewable energy sources. Both energy scenarios are projected under the same future socioeconomic levels but use different assumptions of future energy transition measures (Table A4). The GDP trend was set at 6.0%, 5.5%, and 5.0% per year for the periods 2020−2025, 2025−2030, and 2030−2035, respectively. This is in accordance with the national economic and social development and vision 2035 of Guangzhou City (TPGGM, 2020), which aims for a doubling of per capita GDP by 2035. Details on the BAU and LOC scenarios are discussed in Text A5.

The other dimension explores the levels of air pollution control strategies. Scenarios CLE reflect the continuous impacts of current legislation that has been announced in Guangzhou's air pollution control plans and targets (Table A5). The MFR scenario reflects a strategy of aggressive air pollution control aimed at achieving the maximum feasible reduction. In this scenario, ultralow emission standards for industries, including nonferrous metals, cement, and glass production, would be implemented at levels similar to those of the power sector (Zheng et al., 2018). By 2035, more stringent emission standards would be implemented for on/off-road transport, including China-7 for light- and heavy-duty diesel vehicles and China-3 for shipping. Solvent use sectors are gradually adopting waterborne paints, powder and liquid coatings, as well as incineration and adsorption, to further control VOCs emissions (Liu et al., 2020). Details on the CLE and MFR controls are provided in Text A5. Finally, three future emission scenarios, *i.e.*, the BAU-CLE, BAU-MFR and LOC-MFR scenarios, were created on the basis of various combinations of the aforementioned scenarios.

2.6. Data

The data used mainly include basic social and economic data, energy consumption data, environmental data, and predictive data, which are listed in Table 2. Emission inventories for calibrating simulated emissions of CO_2 and air pollutant, as well as observation data for validating simulated $PM_{2.5}$ and ozone concentrations, are collected from our own database.

3. Results

3.1. Energy consumption patterns and CO_2 emission trajectories

Implementing low-carbon transitions will reshape Guangzhou's energy structure, leading to a substantial reduction in CO_2 emissions. In the BAU and LOC scenarios, energy demand in Guangzhou is expected to increase over the coming decades, driven by the future growth of the economy and population. Owing to existing energy policies, the total final

Table 2
Data sources.

Data	Source
Social and economic data	Guangzhou statistical Yearbook 2021 (GSB, 2021); Guangdong statistical Yearbook 2021 (GPB S, 2021); Resource and Environmental Science Data Platform (https://www.resdc.cn)
Energy data	China Energy statistical Yearbook 2021 (NBS, 2021); Scenario of 'ECLIPSE_V6b_CLE_base' (Klimont et al., 2017; Rafaj et al., 2018)
Environmental data	Guangdong Province Action Plan for Continuous Improvement of Environmental Air Quality (DEEGP, 2021); Guangdong Province Ozone Pollution Control and Prevention Plan by Reducing NO_x and VOCs 2023−2025 (DEEGP, 2022); Action Plan for Efforts to Eliminate Heavy Pollution Weather, Control Ozone Pollution, and Address Diesel Truck Pollution (MEEPRC, 2022)
Predictive data	14th Five-Year Guangzhou Municipal Energy Development (GMDRC, 2022); Outline of the 14th Five-Year Plan (2021−2025) for National Economic and social Development and Vision 2035 of Guangzhou City (TPGGM, 2020); 14th Five-Year Plan for Industry and Information Technology (TPGGM, 2022a), Transportation (TPGGM, 2022b) and Building (GMHURDB, 2022) sector development; 14th Five-Year Guangzhou Municipal Ecological and Environmental Protection (TPGGM, 2022c); Literature (Tong et al., 2021)

energy consumption monotonically increases from 61.5 Mtce in 2020 to 85.6 Mtce in 2035 in the BAU scenario (Fig. 2a). Consequently, CO_2 emissions will continue to increase through 2035, reaching a level 38% higher than that in 2020 (Fig. 2c). However, if the city accelerates the implementation of deep carbon mitigation policies, such as structural adjustments, clean energy substitutions, and energy efficiency improvements, the total final energy use is expected to peak at 72.3 Mtce in 2030 before gradually declining to 67.5 Mtce in 2035 under the LOC scenario. CO_2 emissions will peak at around 106 Mt in approximately 2025 (only 16% higher than the 2020 level) and then decrease to 92 Mt CO_2 in 2035, nearly returning to the 2020 level. Additionally, Guangzhou is projected to achieve its commitment to maintain city CO_2 emission intensity at a leading level in the country by 2030 (TPGGM, 2020), reaching 0.234 t $CO_2/10^4$ CNY (Table A6).

From a sectoral perspective, energy consumption in the power sector will reach 18.4 Mtce in 2035 in LOC, which is 25% lower than that in BAU (Fig. 2b1). The proportion of fossil fuels used in power will decrease from 89% (with coal and gas accounting for 52% and 37%, respectively) in 2020 to 87% in BAU (with coal accounting for 35% and gas accounting for 52%) and to 82% (with coal accounting for 33% and gas accounting for 49%) in LOC by 2035. Moreover, the share of renewable energy (*e.g.*, solar and wind) will increase to 11% in BAU and to 17% in LOC by 2035.

The final energy use in the transportation, building and industrial sectors will be 19.7, 24.3 and 11.7 Mtce, respectively, in 2035 in LOC (Fig. 2b2−b4). These values represent decreases of 8%, 25% and 29%, respectively, compared with those of the BAU scenarios. Oil use in transport is substantially affected: the fraction of oil will decline from 94% in 2020 to 72% in BAU and 58% in LOC in 2035, and this reduction will be paired with a large increase in gas and electricity consumption. The percentage of electricity usage in the building sector is greater than that in other sectors because electrification of end-use service demands in building sectors can be achieved more easily (Isik et al., 2021).

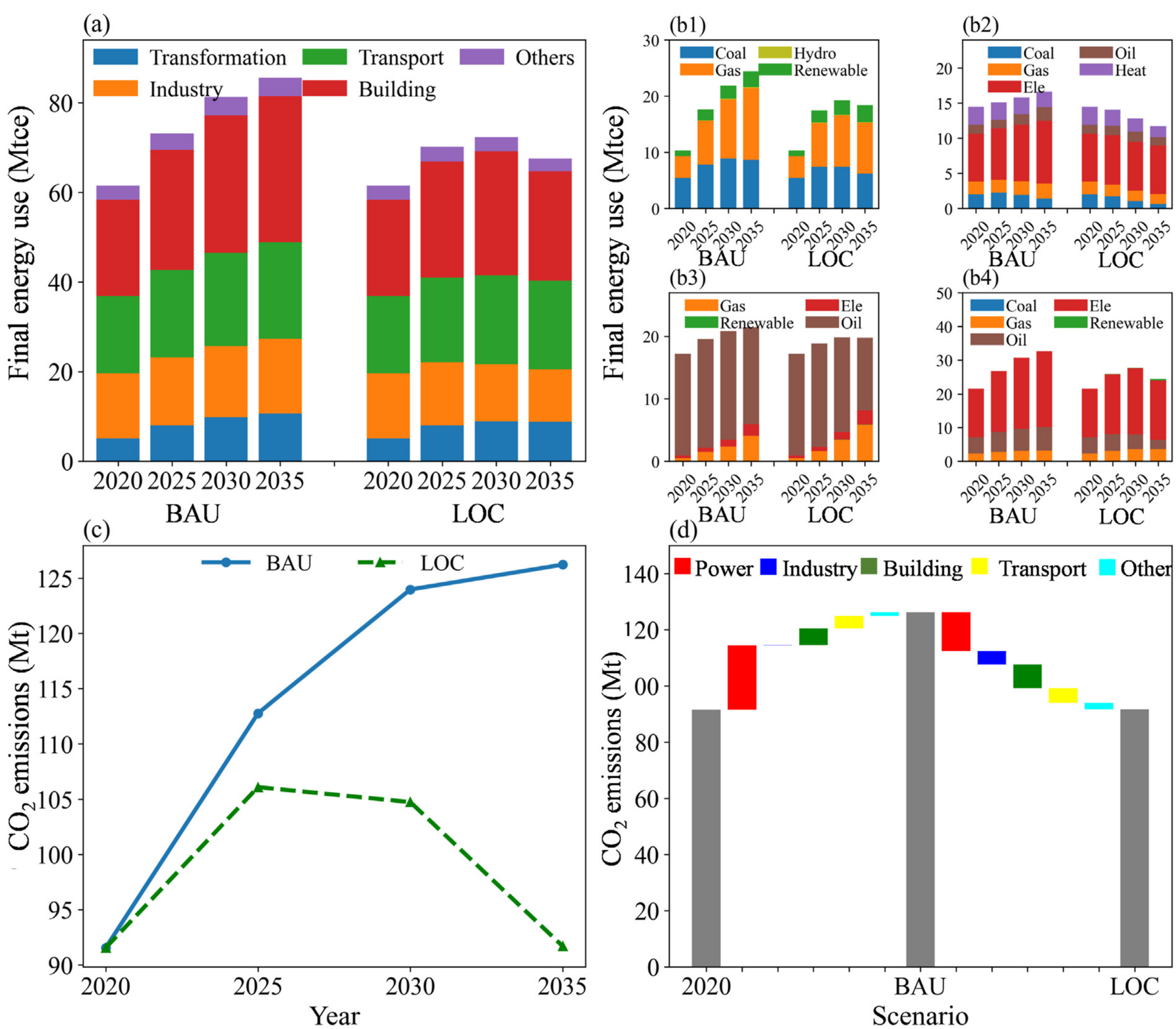

Fig. 2. Energy consumption and CO_2 emissions in Guangzhou from 2020 to 2035, (a) total final energy consumption by sector, energy use in the power (b1), industry (b2), transport (b3) and building (b4) sectors by fuel type, (c) CO_2 emissions, and (d) sectoral contributions to emission reductions between 2020 and the two scenarios in 2035.

In both the BAU and LOC scenarios, the power sector is the dominant driver of changes in CO_2 emissions (Fig. 2d). For example, between 2020 and 2035, almost 65% of the total emission increases in the BAU scenario are obtained from the power sector, driven by growing electricity demand from end-use sectors. In contrast, in the LOC scenario, deep decarbonization of the power generation sector significantly reduces CO_2 emissions, contributing to 40% of the total reduction. The contributions of this sector are followed by those of the building sector (24%), transportation sector (15%) and industrial sector (14%).

3.2. Air pollutant emission reductions

The implementation of air pollutant and CO_2 mitigation leads to varying levels of reduction in air pollutants (Fig. 3a1−a4). Given the existing energy and air pollution policies (BAU-CLE), emissions of primary $PM_{2.5}$, NO_x and VOCs will decline slowly by 2035, whereas SO_2 emissions will exhibit a growing trend during the same period. By achieving the highest levels of air pollution controls (BAU-MFR), the emissions of primary $PM_{2.5}$, SO_2, NO_x and VOCs will decrease from 2020 to 2035, reaching 61%, 71%, 57% and 54% of the values in 2020, respectively. The low-carbon energy policies in LOC-MFR can further reduce the above air pollutant emissions by 47%, 51%, 34%, and 48%, respectively, relative to the 2020 levels. These energy policies limit the use of fossil fuels; therefore, the emissions of air pollutants that primarily derived from fossil fuel, *e.g.*, NO_x and SO_2 (Zheng et al., 2018), have great emission reduction co-benefits of CO_2 mitigation. Because VOCs and primary $PM_{2.5}$ mainly originate from industrial processes (including solvent use) (Fig. A6), the co-benefits of CO_2 reductions on their emissions are not as pronounced as those for NO_x and SO_2.

The emission reductions vary by sector among the different scenarios (Fig. 3b1−b4). For primary $PM_{2.5}$ emissions, the industry is an important sector of emission cuts because of the application of advanced end-of-pipe technologies. Compared with the 2020 levels, the reductions in the $PM_{2.5}$ emissions from the industrial sector in 2035 in BAU-CLE and BAU-MFR will be 4.8 and 8.7 kt, accounting for 61% and 65% of the total emission reductions, respectively. In LOC-MFR, substitutions of clean energy and improvements in energy efficiency within the transport and building sectors will further reduce $PM_{2.5}$ emissions by 1.7 and 1.6 kt, respectively. For SO_2, emissions from all the sectors increase in BAU-CLE because no additional control policies are applied from 2020 to 2035. With the implementation of all feasible end-of-pipe controls, the industrial sector remains a main source of reduction in SO_2 emissions. In LOC-MFR, the power and building sectors are expected to reduce SO_2 emissions by 78% from the BAU-MFR scenario in 2035. This reduction is attributed mainly to the development of clean and renewable energy sources and the decline in energy consumption in buildings.

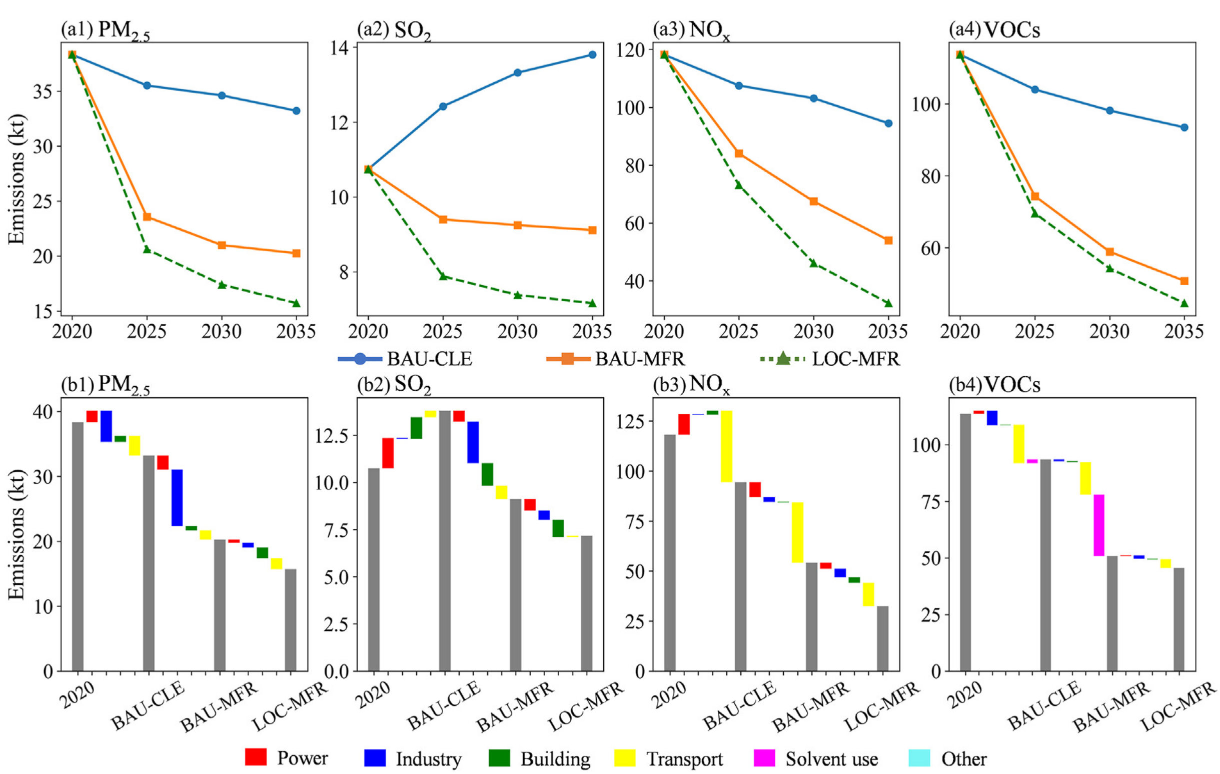

Fig. 3. Air pollutant emissions in Guangzhou from 2020 to 2035, primary $PM_{2.5}$ (a1), SO_2 (a2), NO_x (a3), and VOCs (a4) under different scenarios, and sectoral contributions to primary $PM_{2.5}$ (b1), SO_2 (b2), NO_x (b3), and VOC (b4) emission reductions between 2020 and the two scenarios in 2035.

The NO_x emission reductions under the BAU-CLE, BAU-MFR and LOC-MFR scenarios are attributed mainly to the transportation sector through the following mechanisms: optimizing the transportation mode share; encouraging the shift of freight service demands from on-road transport to rail and water transport; popularizing clean and new-energy vehicles; and strengthening emission standards for on-road and nonroad mobile machinery. The contribution of this sector to reducing NO_x ranges between 54% and 82% under alternative scenarios. For VOCs, the solvent use and transportation sectors will drive the emission reductions because of the application of more effective end-of-pipe measures. Nevertheless, the reductions from the transport will be implemented primarily in BAU-CLE, whereas the reductions from the solvent use will become the main source in BAU-MFR. In LOC-MFR, the transportation sectors will reduce VOCs emissions by 69% from the BAU-MFR scenario in 2035.

3.3. Air quality improvements

Implementing mitigation policies has contrasting impacts on $PM_{2.5}$ and ozone concentration, delivering significant improvements in $PM_{2.5}$ levels while increasing ozone concentrations. Fig. 4 shows the simulated annual mean $PM_{2.5}$ and MDA8 ozone concentrations for 2020, the projected concentrations in the BAU-CLE scenario for 2035, and the reductions in the BAU-MFR and LOC-MFR scenarios in 2035 compared with those in the BAU-CLE scenario. As shown in Fig. 4a, in both 2020 and 2035, the highest $PM_{2.5}$ concentration levels (BAU-CLE) are estimated for the western part of Guangzhou (particular in winter, Fig. A7), where the city's emission intensity is greatest (Wu et al., 2021; Zhang et al., 2023). In 2020, the annual population-weighted mean $PM_{2.5}$ concentration (unless specified otherwise, the air pollutant concentrations reported hereafter refer to population-weighted air pollutant concentrations.) was 28 μg/m^3 in Guangzhou. The implementation of pollution control measures will lead to improvements in the $PM_{2.5}$ concentration, whereas a strengthened carbon mitigation policy will yield greater improvements in air quality in a larger region. For example, the $PM_{2.5}$ concentration in the BAU-MFR scenario is 24 μg/m^3 in 2035, which is 2 μg/m^3 lower than that in the BAU-CLE scenario, whereas in the LOC-MFR scenario, it decreases to 21 μg/m^3, which is 5 μg/m^3 lower. A more prominent reduction will occur in more polluted areas (Fig. 4a3−a4).

Contrasting the $PM_{2.5}$concentration, the concentration of ozone increases with the implementation of mitigation policies. As shown in Fig. 4b1−b4, relatively high MDA8 ozone concentrations appear in the northern parts of Guangzhou (particular in summer, Fig. A8) in 2020 and 2035 (BAU-CLE). The annual population-weighted mean MDA8 ozone concentration in 2020 was 132 μg/m^3. By 2035, the value in Guangzhou will increase by 14% from 148 μg/m^3 under the BAU-CLE scenario to 169 μg/m^3 under the BAU-MFR scenario and further increase to 183 μg/m^3 under the LOC-MFR scenario. These ozone increases are most noticeable in winter

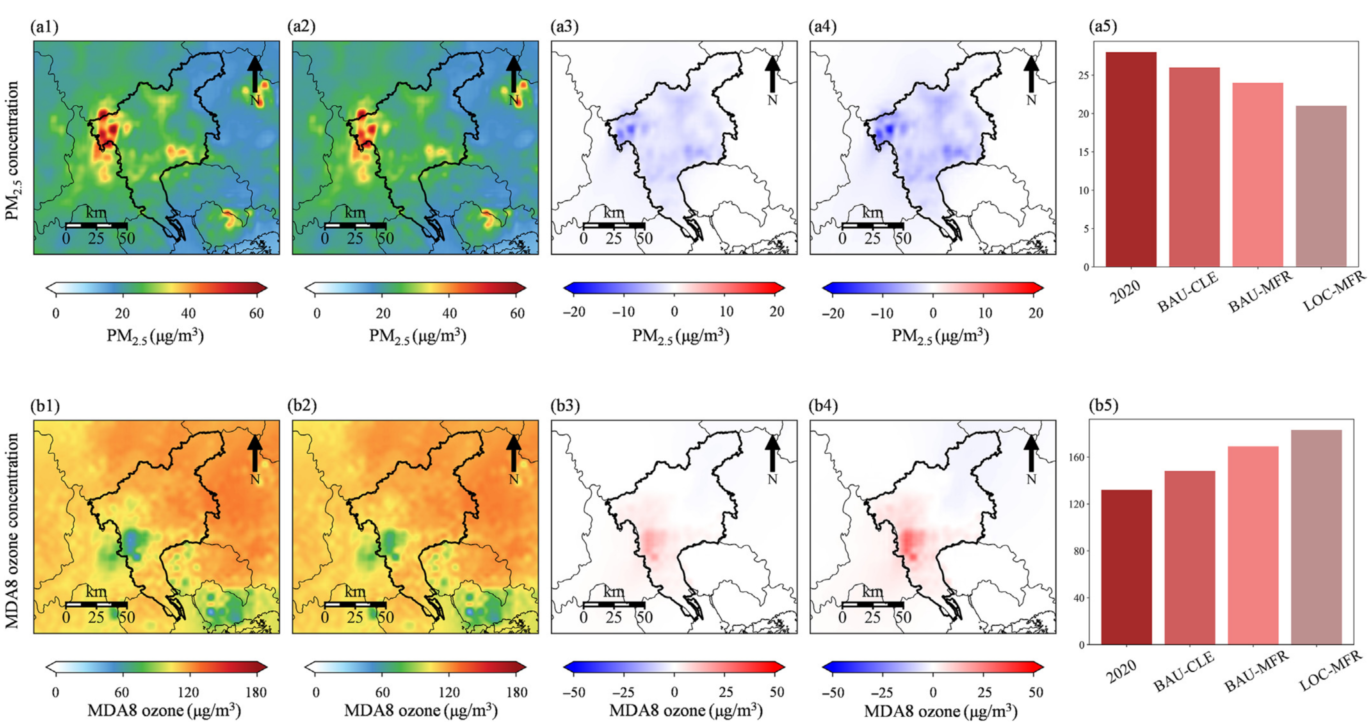

Fig. 4. Spatial distribution of the $PM_{2.5}$ concentration in 2020 (a1) and 2035 under the BAU-CLE scenario (a2), as well as changes in 2035 under the BAU-MFR (a3) and LOC-MFR (a4) scenarios compared with the BAU-CLE scenario, and annual population-weighted mean $PM_{2.5}$ concentrations in 2020 and 2035 under different scenarios (a5); and spatial distribution of the MDA8 ozone concentration in 2020 (b1) and 2035 under the BAU-CLE scenario (b2), as well as changes in 2035 under the BAU-MFR (b3) and LOC-MFR (b4) scenarios compared with the BAU-CLE scenario, and annual population-weighted mean MDA8 ozone concentrations in 2020 and 2035 under different scenarios (b5).

(Fig. A9) when they reach upwards of 15 μg/m^3 over the majority of southern cities. Unlike the formation of secondary $PM_{2.5}$, ozone formation can be divided into VOC-limited (commonly in urban areas) and NO_x-limited (commonly in rural areas) regimes. In winter, the titration of ozone by NO becomes more important due to the lower NO_2 photolysis rate compared to summer. The implementation of mitigation measures in Guangzhou city, *i.e.*, the VOC-limited region, can reduce the titration effect of NO to ozone ($NO + O_3 = NO_2 + O_2$), leading to unwanted increases in surface ozone concentrations, especially in winter.

3.4. Health impacts

Exposure to $PM_{2.5}$ and ozone raises the risk of mortality from various diseases. Fig. 5 shows the trends of annual $PM_{2.5}$- and ozone-related premature deaths under the different scenarios, as well as the number of avoided excess deaths under the two policy scenarios relative to the baseline scenario. In 2020, the number of premature deaths attributable to $PM_{2.5}$ exposure in Guangzhou was estimated at 11.6 thousand (95% CI: 7.2−15.5), and IHD led to the most premature mortality, followed by LRIs (Table A7). In 2035, the number will increase to 18.9 thousand (95% CI: 12.3−24.9) in BAU-CLE; then, it will decrease to 17.7 thousand (95% CI: 11.6−23.4) in BAU-MFR and 15.9 thousand (95% CI: 10.5−21.1) in LOC-MFR. Despite the decreasing annual population-weighted mean $PM_{2.5}$ levels, premature deaths are projected to rise under various scenarios compared with 2020 levels, mainly due to the growth and ageing of the population (Zheng et al., 2019). The mortality of ozone in 2020 would be lower than that of $PM_{2.5}$, with the total number of deaths calculated at 2.6 thousand (95% CI: 1.3−4.9), and RESP and CVD would contribute 0.5 thousand (0.2−0.9) and 2.1 thousand (1.1−4.0), respectively. Owing to demographic changes and increased ozone concentrations, by 2035, the corresponding number of premature deaths will be 3.9 thousand (95% CI: 2.0−7.4), 4.9 thousand (95% CI: 2.5−9.2) and 5.5 thousand (95% CI: 2.8−10.3) in BAU-CLE, BAU-MFR and LOC-MFR, respectively, which is 1−2 times greater than the 2020 level.

Compared with the BAU-CLE scenario, the BAU-MFR and LOC-MFR scenarios prevent 1.2 thousand (95% CI: 0.6−1.6) and 3.0 thousand (95% CI: 2.0−3.9) $PM_{2.5}$-related premature deaths, respectively, in Guangzhou in 2035. However, these two scenarios also result in 1.0 thousand (95% CI: 0.2−1.9) and 1.6 thousand (95% CI: 0.7−2.7) more cases of ozone-related premature deaths, respectively (Fig. 5c). Since the population continues to grow and age, it is crucial to take further action to effectively reduce both $PM_{2.5}$ and ozone pollution. This includes implementing multiregional integrated controls to ensure improved overall health benefits.

3.5. Regional coordinated emission controls

Implementing multiregional integrated control measures in Guangzhou and its neighbouring cities yields greater air quality and health benefits for Guangzhou compared to local enforcement alone. We further examine the implications for air quality and related mortality in Guangzhou in 2035 if not only Guangzhou city but also the other seven neighbouring cities, Foshan, Zhaoqing, Shenzhen, Dongguan, Huizhou, Zhuhai, Zhongshan and Jiangmen, aggressively reduce air pollutant emissions according to the LOC-MFR scenario. The implementation of the multiregional emission control strategy described above (*i.e.*, the LOC-MFR-REC scenario) is conducive to further improving air quality in Guangzhou. For example, under the LOC-MFR-REC scenario, the population-weighted concentrations of $PM_{2.5}$ and MDA8 ozone in 2035 are 19 and 160 μg/m^3, respectively, which are 2 and 23 μg/m^3 lower than those under the LOC-MFR scenario (Fig. 6). This finding is consistent with those of previous studies, which revealed the importance of cooperative emission control strategies for alleviating $PM_{2.5}$ and ozone pollution. Moreover,

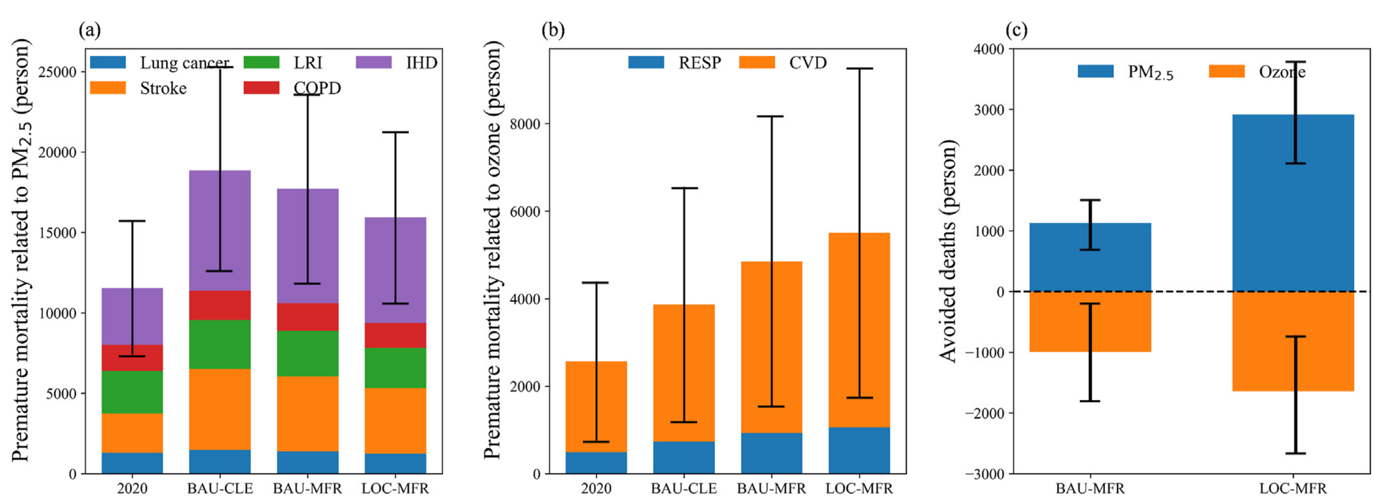

Fig. 5. $PM_{2.5}$ (a) and ozone-related (b) premature deaths in 2020 and 2035 under different scenarios, and (c) changes in premature deaths from both pollutants in 2035 under the BAU-MFR and LOC-MFR scenarios compared with the BAU-CLE scenario (The negative horizontal axis refers to an increase in premature deaths).

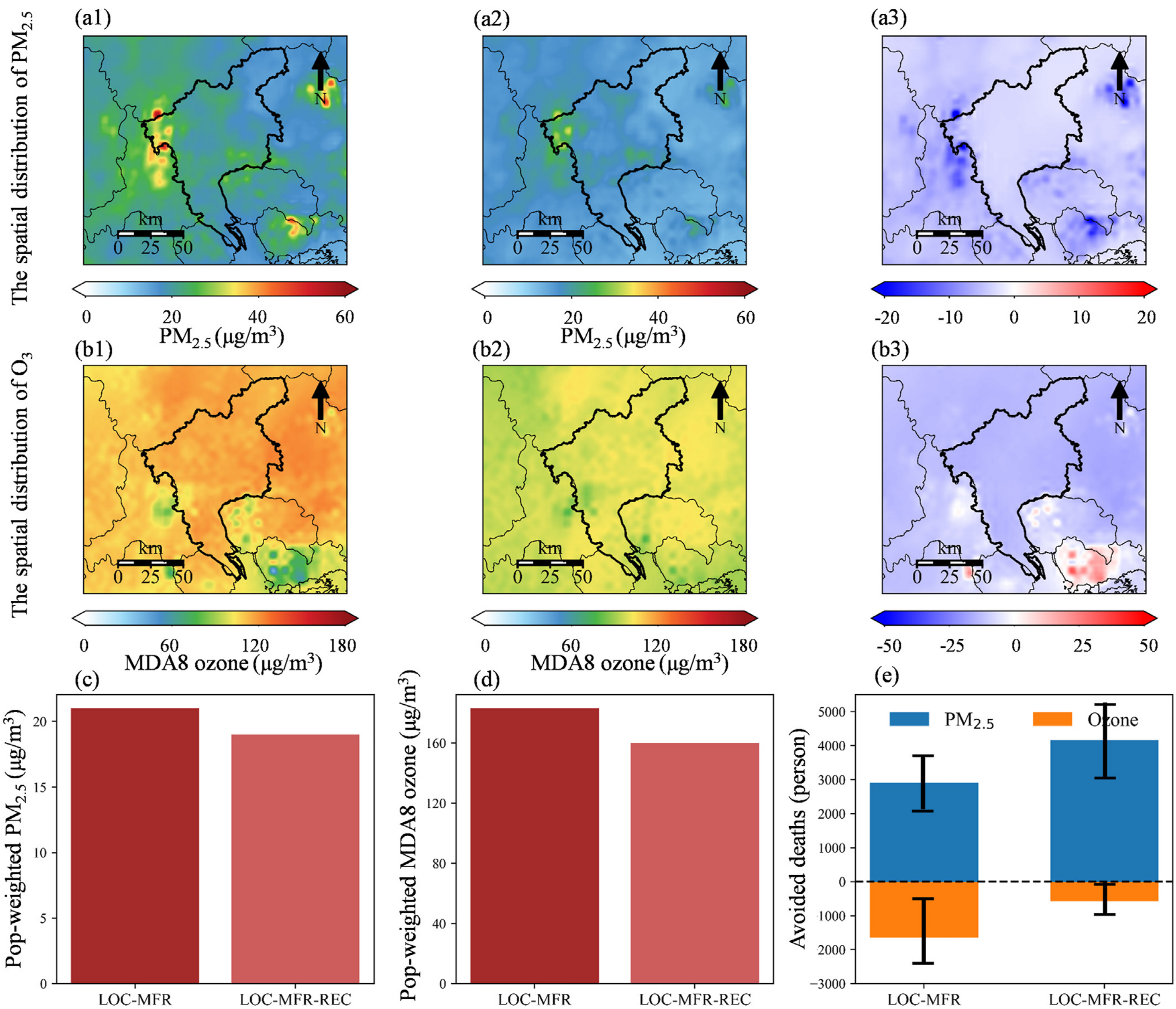

Fig. 6. Spatial distribution of $PM_{2.5}$ concentrations in 2035 under LOC-MFR (a1) and LOC-MFR-REC (a2) scenarios, as well as changes between these two scenarios (a3); (b) spatial distribution of MDA8 ozone concentrations in 2035 under LOC-MFR (b1) and LOC-MFR-REC (b2) scenarios, as well as changes between these two scenarios (b3); annual population-weighted mean (c) $PM_{2.5}$ and (d) MDA8 ozone concentrations in 2035 under different scenarios; and (e) changes in premature deaths from both pollutants in 2035 under LOC-MFR and LOC-MFR-REC scenarios compared with the BAU-CLE scenario (The negative horizontal axis refers to an increase in premature deaths).

greater health benefits can be achieved through regional cooperation. For example, when compared to the BAU-CLE scenario, the LOC-MFR-REC scenario—implementing multiregional integrated controls—can prevent approximately 4.2 thousand (95% CI: 3.3–5.2) $PM_{2.5}$-related premature deaths, nearly 1.5 times more than the LOC-MFR scenario. Simultaneously, these cooperative emission control strategies result in only 0.5 thousand (95% CI: 0.1–1.0) additional ozone-related premature deaths, which is merely 0.3 times the figure observed with local enforcement alone. These findings highlight the importance of implementing regional cooperation to effectively reduce the overall public health burden in populous cities.

We summarize the key findings from CO_2 emissions, air quality, and health impact assessments across the three policy scenarios (BAU-MFR, LOC-MFR, and LOC-MFR-REC) in Table 3. Under the LOC-MFR scenario, CO_2 emissions are reduced by 28% compared to the BAU-CLE scenario, while $PM_{2.5}$ concentrations decrease by 5 $\mu g/m^3$, leading to 3.0 thousand (95% CI: 2.0–3.9) avoided premature deaths. However, ozone concentration rise by 35 $\mu g/m^3$, resulting in an additional 1.6 thousand (95% CI: 0.8–2.9) ozone-related deaths. Under the LOC-MFR-REC scenario, greater air quality and health benefits are achieved relative to the BAU-CLE scenario, namely reductions of 7 $\mu g/m^3$ in $PM_{2.5}$ and -12 $\mu g/m^3$ in ozone concentrations, as well as decreases of

Table 3
Summary of changes in CO_2 emissions, $PM_{2.5}$ and ozone concentration, and associated premature deaths in 2035 under different policy scenarios relative to the 2035 BAU-CLE scenario.

Scenario	CO_2 reduction (%)	$PM_{2.5}$ reduction (μg/m^3)	Avoided $PM_{2.5}$ death (thousand person)	Ozone reduction (μg/m^3)	Avoided ozone death (thousand person)
BAU-MFR	0	2	1.2 (0.6−1.6)	−21	−1.0 (0.5−1.8)
LOC-MFR	28	5	3.0 (2.0−3.9)	−35	−1.6 (0.8−2.9)
LOC-MFR-REC	28	7	4.2 (3.3−5.2)	−12	−0.5 (0.1−1.0)

Note: Considering only direct emissions within city boundaries. The negative values indicate an increase in concentrations and premature deaths.

4.2 thousand (95% CI: 3.3−5.2) $PM_{2.5}$-related premature deaths and −0.5 thousand (95% CI: 0.1−1.0) ozone-related premature deaths.

3.6. Impacts on emission control costs

Emission control technology reduces emissions but comes at a cost. GAINS model calculates the additional expenditures required to install and operate the end-of-pipe technologies. It excludes transfer payments like subsidies, taxes and profits, and offsets initial investments with subsequent cost savings, such as those from reduced energy consumption (Amann et al., 2011). Fig. 7 illustrates the increased costs by key sectors for alternative scenarios compared with the BAU-CLE scenario in 2035. Adopting a stricter air pollution control technology will result in higher air pollutant control costs. In comparison with the BAU-CLE scenario, the BAU-MFR scenario will lead to an increase of 2570 million EUR (using 2005 level) in control cost. The transportation sector accounts for the largest share of incremental costs, followed by the industrial sector. Low-carbon energy and industrial transitions will induce cost savings for air pollution control or, in other words, avoid expenses for air pollution control. In moving from BAU-MFR to LOC-MFR in 2035, the decrease in the air pollution control cost will be 100 million EUR. More than 60% of cost savings are associated with the building and transport sectors.

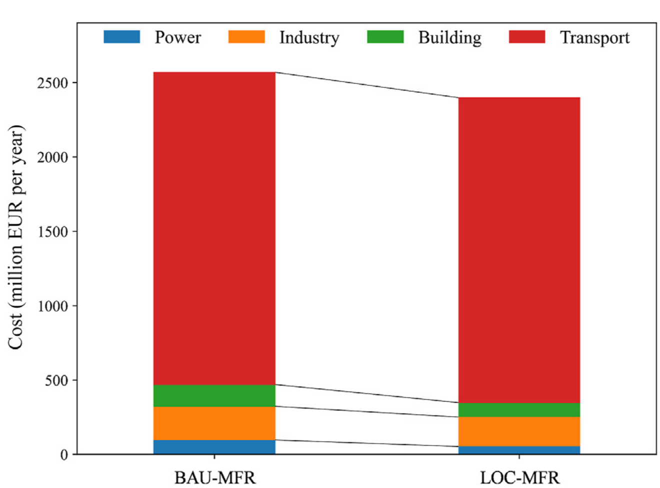

Fig. 7. Incremental air pollution control cost in the BAU-MFR and LOC-MFR scenarios compared with that in the BAU-CLE scenario in 2035.

4. Discussion

We advance existing research by offering a detailed evaluation of how low-carbon transitions and stringent air pollution controls collectively impact $PM_{2.5}$ and ozone concentrations in Guangzhou. Unlike previous studies, which have not fully quantified these effects at the city level, this work provides a comprehensive urban-scale assessment. In agreement with earlier studies (Cheng et al., 2021; Tong et al., 2019; Zhang et al., 2021), we project that, in addition to aggressive air pollution control policies, the introduction of deep carbon mitigations has the potential to further reduce air pollutant emissions, thereby increasing the co-benefits for $PM_{2.5}$ air quality and associated public health. However, when the effects of both $PM_{2.5}$ and ozone are considered, the effectiveness of emission control policies in alleviating the health burden from air pollution is limited. This is because implementing mitigation policies in Guangzhou can reduce the titration effect of NO to ozone, leading to an increase in ozone exposure that partially offsets the health co-benefits induced by the reduction in $PM_{2.5}$. Thus, when advancing the synergistic management of CO_2 emissions and air pollution, it is crucial to focus on coordinating the control of $PM_{2.5}$ and ozone to maximize health benefits.

Our results further imply that implementing multiregional integrated control measures in Guangzhou and its neighbouring cities yields greater air quality and health benefits for Guangzhou than does local enforcement alone. Specifically, the LOC-MFR-REC scenario leads to 1.5 times more avoided $PM_{2.5}$-related premature deaths and results in 0.3 times fewer additional ozone-related premature deaths, compared to the LOC-MFR scenario. Thus, the application of multiregional integrated control strategies in neighbouring cities proves to be the most effective approach for reducing air pollution and mitigating associated health impacts.

The sectoral analysis reveals that the transportation and industrial sectors play a dominant role in emissions reduction. However, solvent-related VOCs control must be prioritized to address ozone pollution. These insights align with findings in other megacities, such as Beijing and Shanghai, and offer actionable strategies for coordinated urban and regional management.

4.1. Policy implications

First, our results indicate that optimizing the transportation mode share and accelerating the adoption of electric vehicles

(EVs) can substantially reduce both NO_x and VOCs emissions. The model simulations show that enhanced nonmotorized and public transport usage in Guangzhou could decrease local emission by up to 50% (see Section 3.2). For urban passenger transport, enhancing the proportion of green transport, such as cycling, walking and public transport, has been emphasized in many other megacities, including Beijing, Shanghai and Tianjin in China (Lu et al., 2022; Tian et al., 2018); London in the UK (Chaudry et al., 2022); and Delhi in India (Abdul-Manan et al., 2022). Thus, Guangzhou and surrounding cities should promote the construction of nonmotorized transport and high-throughput convenient public transport infrastructure to ensure that reducing private car use does not lead to reduced mobility. With respect to freight transport, emission reductions will depend mainly on optimizing the freight structure and improving logistics. In particular, the current emphasis on promoting railway and waterway freight transport, the large-scale expansion of the logistics industry, and the development of an integrated freight transportation system in Guangzhou are all positive steps in the right direction (TPGGM, 2022,b,c). In addition to these strategies, the adoption of electric vehicles (EVs) is recommended to be an effective option for addressing both air pollutant and greenhouse gas reduction goals (TPGGM, 2022,b,c; Wu et al., 2021b; Zhang et al., 2023). According to the 13th Five-Year Plan of Comprehensive Transportation for Guangzhou (TPGGM, 2016), the city set a goal to fully electrify buses and taxis by 2020. The unicipal government is thus advised to expand EVs adoption in municipal services, urban logistics, and private vehicles. Given the withdrawal of initial purchase incentives after 2020, local authorities can offer yearly incentives for EV owners based on the health benefits derived from their actual electric vehicle usage. Moreover, Guangzhou and neighbouring cities need to closely collaborate to electrify fleets and update emission standards so that health benefits can be maximized. This collaboration can include planning for charging infrastructure and battery swapping networks, cultivating emerging industries (*e.g.*, charging infrastructure management and battery recycling) and enforcing stricter regulations on fuel efficiency, oil quality, and emissions.

Second, our analysis of industrial sectors in Guangzhou demonstrates that the rapid implementation of ultralow emission standards can lead to substantial reductions in key pollutants. For instance, our simulation indicates that stringent controls in the iron, steel, and cement industries could reduce local $PM_{2.5}$ emissions by up to 60% relative to baseline conditions. The quick promotion of ultralow emission standards is crucial for pollution control in industrial sectors (Zhang et al., 2019). In fact, Guangzhou and its surrounding cities planned to complete ultralow emission transformation for iron and steel plants by 2022 and for cement plants by 2025 and planned to implement in-depth controls for the glass, foundry, and lime industries (TPGGM, 2022). For municipal governments, the top priority is to ensure the prompt and thorough implementation of these measures. An appropriate pollution monitoring system needs to be put in place to facilitate the implementation of these policies. In particular, the Ministry of Ecology and Environment (MEE) has developed a continuous emission monitoring system (CEMS) to measure facility-level, real-time smokestack concentrations. CEMS data have now been used by regulatory authorities to evaluate air pollutant emissions from power units and iron and steel plants (Bo et al., 2021). However, data from other high-emitting industries, such as cement and plate glass plants, have not yet been assessed. To further alleviate industrial air pollution, the CEMS network should be extended to cover these sectors, which have relatively low emission standards. Moreover, economic instruments such as an emissions trading scheme, which has proven effective in reducing carbon emissions (NDRC, 2017), might complement the above standards.

Third, we reveal that strong control of solvent-related VOCs emissions is necessary to counterbalance the unintended consequences of reduced NO_x in mitigating ozone pollution. Previous studies have indicated that ozone formation in megacities like Beijing, Shenzhen and Tianjin, generally has VOC-limited conditions (Lu et al., 2018; Wang et al., 2021). Reductions in NO_x could increase urban-averaged ozone concentrations, whereas controls on VOCs emissions generally decrease ozone concentrations. Given the increasing importance of future low-carbon policies, the constant strengthening of NO_x reductions is inevitable. Therefore, independent VOCs abatement in response to NO_x control is vital for mutual control of $PM_{2.5}$ and ozone. In addition to transport, the solvent use sector is another notable contributor to VOCs abatement in Guangzhou (Fig. 3), mainly because of the application of advanced end-of-pipe measures. Fugitive emissions are the primary contributors in this sector. Controlling these emissions is both costly and resource-intensive (DEEGP, 2022). In 2019, the MEE issued a standard for fugitive emission of VOCs (GB37822−2019). However, some enterprises, especially poorly managed small and medium-sized ones, may refuse to implement national emission standards to avoid increasing their production costs. Therefore, it is recommended that local governments install CEMs for VOCs and connect them to the monitoring system to oversee the high-emitting enterprises.

Finally, despite not being a significant contributor to reductions for air pollutants and CO_2 in Guangzhou, the building sector has a substantial indirect effect, as electricity is its primary source of energy use, accounting for nearly 63% of Guangzhou's overall electricity use (Fig. A10). Therefore, saving electricity in buildings indirectly contributes to reducing local or regional air pollutants and CO_2 emissions by reducing power demand. However, Guangzhou's building energy use per unit area in 2020 was only approximately 80% of the average level in developed countries (GMHURDB, 2022). To further increase energy efficiency, superefficient equipment and appliances should be promoted for residential and commercial buildings, with a focus on heating, cooking, and various end-uses, such as appliances, cooling and lighting. In addition, clean energy utilization is crucial. In 2020, buildings in Guangzhou predominantly used electricity and LPG for energy (TPGGM, 2021). Thus, increasing the use of electricity generated from low-polluting fuels, promoting natural gas

Table 4
$PM_{2.5}$- and ozone-related premature deaths via different ERFs.

Title		2020	BAU-CLE	BAU-MFR	LOC-MFR	LOC-MFR-REC
$PM_{2.5}$-related (thousand person)	GEMM (5 diseases)	11.6 (7.2, 15.2)	18.9 (12.3, 24.9)	17.7 (11.6, 23.4)	15.9 (10.5, 21.1)	14.7 (9.7, 19.4)
	IER (5 diseases)	8.7 (5.4, 11.1)	15.2(10.1, 21.2)	14.3 (9.3, 19.8)	12.6 (7.9, 17.9)	11.3 (6.8, 15.7)
	Log-linear (all cause)	14.1 (7.7, 22.1)	21.6 (10.9, 32.2)	20.3 (9.3, 31.1)	18.2 (7.5, 29.6)	17.6 (6.3, 28.5)
ozone-related (thousand person)	Turner et al. (2016)	2.6 (1.3, 4.9)	3.9 (2.0, 7.4)	4.9 (2.5, 9.2)	5.5 (2.8, 10.3)	4.4 (2.3, 8.4)
	Jerrett et al. (2009)	1.1 (0.3, 3.1)	2.4 (1.0, 5.9)	3.5 (2.1, 7.8)	4.2 (2.3, 8.9)	3.1 (1.9, 6.5)

Note: The values in parentheses represent 95% confidence intervals.

over LPG, and installing rooftop solar photovoltaic systems will be beneficial.

While these policy implications are directly derived from our Guangzhou case study, the integrated framework and modelling approach developed here offer a transferable tool for urban air quality and climate policy assessment in other megacities and regions. By demonstrating how targeted interventions in transportation, industry, VOCs control, and building energy use can synergistically improve environmental outcomes, our study provides a practical roadmap for policymakers globally to balance carbon reduction and air quality improvements.

4.2. Uncertainties and limitations

The selection of ERFs can introduce uncertainties into health risk assessments, so we applied three ERFs (*i.e.*, GEMM (Burnett et al., 2018), IER (Stanaway et al., 2018) and log-linear (Pope et al., 2002) functions) for $PM_{2.5}$ and two (*i.e.*, ERFs from Turner et al. (2016) and Jerrett et al. (2009)) for ozone to estimate premature deaths in Guangzhou under different scenarios and analysed their potential uncertainties (Table 4). With respect to $PM_{2.5}$, the number of premature deaths estimated via the GEMM or log-linear functions is greater than that estimated via the IER functions. Quantitatively, in 2020, premature mortality was estimated to be 11.6 thousand (95% CI: 7.2, 15.2), 14.1 thousand (95% CI: 7.7, 22.1) and 8.7 thousand (95% CI: 5.4, 11.1), when the GEMM, log-linear and IER functions were used, respectively. In the 2035 scenario, the central estimates of $PM_{2.5}$-related deaths increase to 14.7−18.9 thousand on the basis of the GEMM functions, 17.6−21.6 thousand on the basis of the log-linear functions, and 11.3−15.2 thousand on the basis of the IER functions. With respect to ozone, the premature deaths estimated via ERFs from Turner et al. (2016) are greater than those estimated from Jerrett et al. (2009) because of improved exposure models and a larger dataset that includes observations of more participants over a longer period in the former. For example, the number of additional deaths estimated with the Turner et al. (2016) model is approximately 1−2 times greater than that estimated with the Jerrett et al. (2009) model under various scenarios. However, our key findings are robust: mitigation policies adopted only in Guangzhou offer limited $PM_{2.5}$ and ozone-related health benefits, while notably greater health improvements can be achieved for Guangzhou through synergistic governance with surrounding cities. In addition, we estimated mortality via national baseline mortality rates rather than city-based rates and assumed unchanged in the spatial distribution of the baseline mortality rates or population in 2035. Such assumptions might lead to a certain degree of uncertainty.

Additionally, there are two other uncertainties in estimating future emissions and air quality. First, the evolution of future CO_2 and air pollutant emissions was estimated by connecting the LEAP and GAINS models. On the one hand, we projected energy consumption and CO_2 emissions on the basis of the energy scenario derived from the LEAP, which is occasionally not in line with Guangzhou's current energy development planning. On the other hand, since the air pollution policies promulgated by governments typically include macrolevel measures without detailed parameterized actions, the air pollutant emissions calculated by the GAINS may deviate from the actual situation because of the parameterization process within each scenario. Second, the air quality simulated by the WRF-CAMx model is unavoidably affected by the inherent uncertainties in the model's representation of chemical and physical processes. However, comparisons between observations and simulations indicate that our model accurately captures the temporal and spatial patterns of $PM_{2.5}$ and ozone concentrations across Guangzhou for 2020 (Table A3 and Fig. A5). Moreover, WRF-CAMx is used to derive relative changes in pollution exposure through differential analysis, which may partially eliminate model uncertainties. Furthermore, in addition to the influence of neighbouring cities, the future air quality in Guangzhou is influenced by other provinces or countries (Yu et al., 2019). Our regional joint prevention and control scenario assumes only emission reductions for Guangzhou and neighbouring cities while neglecting the impacts from other regions. The cooperative emission reduction scenario in the next phase should also consider reductions for regions other than Guangdong Province.

5. Conclusions

The LEAP-Guangzhou model, the GAINS model, the WRF-SMOKE-CAMx model and the GEMM model are linked to quantitatively evaluate the air quality and health impacts of carbon reduction and air pollution control measures on both $PM_{2.5}$ and ozone in Guangzhou, a megacity in China. By 2035, primary $PM_{2.5}$, SO_2, NO_x and VOCs emissions will decline by approximately one-third in the aggressive air pollution control scenario compared with those in 2020. These emissions are more than halved when air pollution controls are combined with low-carbon energy policies. With the implementation of both deep carbon mitigation and aggressive air pollution control policies, the population-weighted $PM_{2.5}$ concentration in 2035 will be reduced by 5 μg/m^3 compared with that in the baseline scenario, while the ozone concentration will increase by 35 μg/m^3 owing to the reduced titration effect of NO on ozone. As a result, the reduction in $PM_{2.5}$ could prevent 3.0 thousand premature deaths, whereas the increase in ozone might lead to an additional 1.6 thousand premature deaths. Moreover, the application of multiregional integrated control measures in Guangzhou and its neighbouring cities yields greater air quality and health benefits for Guangzhou than local enforcement alone, resulting in 1.5 times more avoided $PM_{2.5}$-related premature deaths. Additionally, the increase in ozone-related premature deaths from these cooperative emission control strategies is merely 0.3 times the figure observed under local enforcement alone. At the sectoral level, the transportation sector is a major contributor to the reduction in NO_x and VOCs emissions, whereas the industrial sector plays a key role in reducing emissions of primary $PM_{2.5}$ and SO_2. The implementation of end-of-pipe controls in the solvent use sector can be another notable contributor to VOCs abatement, which can offset the side effects of reduced NO_x in mitigating ozone pollution. In addition to bringing co-reductions in air pollutant emissions, low-carbon energy transitions have an added co-benefit of reducing air pollution control costs.

Declaration of competing interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Yun Shu: Writing − review & editing, Writing − original draft, Supervision, Conceptualization. **Yang Li:** Software, Resources, Data curation. **Yazhen Wu:** Software, Resources, Investigation. **Xiang-Zhao Feng:** Resources, Methodology. **Sha-Sha Xu:** Software, Data curation. **Ya-Li Wang:** Formal analysis. **Tong Ma:** Software, Resources. **Jian-Hua Chen:** Investigation, Conceptualization. **Jian Gao:** Supervision. **Shaohui Zhang:** Investigation. **Ji-Zhang Huang:** Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.accre.2025.03.010.

References

Abdul-Manan, A.F.N., Gordillo Zavaleta, V., Agarwal, A.K., et al., 2022. Electrifying passenger road transport in India requires near-term electricity grid decarbonisation. Nat. Commun. 13, 2095−2103. https://doi.org/10.1038/s41467-022-29620-x.

Amann, M., Bertok, I., Borken-Kleefeld, J., et al., 2011. Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications. Environ. Model. Software 26, 1489−1501. https://doi.org/10.1016/j.envsoft.2011.07.012.

Atkinson, R.W., Butland, B.K., Dimitroulopoulou, C., et al., 2016. Long-term exposure to ambient ozone and mortality: a quantitative systematic review and meta-analysis of evidence from cohort studies. BMJ Open 9493−9499. https://doi.org/10.1136/bmjopen-2015-009493.

Bo, X., Jia, M., Xue, X., et al., 2021. Effect of strengthened standards on Chinese ironmaking and steelmaking emissions. Nat. Sustain. 4, 811−820.

Burnett, R., Chen, H., Szyszkowicz, M., et al., 2018. Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. Proc. Natl. Acad. Sci. 115, 9592−9597. https://doi.org/10.1073/pnas.1803222115.

Chaudry, M., Jayasuriya, L., Blainey, S., et al., 2022. The implications of ambitious decarbonisation of heat and road transport for Britain's net zero carbon energy systems. Appl. Energy 305, 117905−117914. https://doi.org/10.1016/j.apenergy.2021.117905.

Chen, D., Zhang, Y., Lang, J., et al., 2019. Evaluation of different control measures in 2014 to mitigate the impact of ship emissions on air quality in the Pearl River Delta, China. Atmos. Environ. 216, 116911−116919. https://doi.org/10.1016/j.atmosenv.2019.116911.

Cheng, J., Tong, D., Zhang, Q., et al., 2021. Pathways of China's $PM_{2.5}$ air quality 2015−2060 in the context of carbon neutrality. Natl. Sci. Rev. 8, 78−85. https://doi.org/10.1093/nsr/nwab078.

DEEGP (Department of Ecology and Environment of Guangdong Province), 2021. Announcement for Guangdong Province Ozone Pollution Control and Prevention Plan by Reducing NO_x and VOCs 2023−2025. http://gdee.gd.gov.cn/wj5666/content/post_4097395.html.

DEEGP, 2022. Announcement for Guangdong Province Action Plan for Continuous Improvement of Environmental Air Quality 2021−2025. http://gdee.gd.gov.cn/zwxx_1/content/post_3844734.html (accessed Dec 15.2023).

GPBS (Guangdong Provincial Bureau of Statistics), 2021. Guangdong Statistical Yearbook 2021. China Statistics Press, Guangzhou.

GMDRC (Guangzhou Municipal Development and Reform Commission), 2022. Announcement for "14th Five-Year". http://fgw.gz.gov.cn/fzgg/fzgh/content/post_8591199.html (accessed 15 Dec 2023).

GMHURDB (Guangzhou Municipal Housing and Urban-Rural Development Bureau), 2022. Guangzhou Green Building Development Special Plan (2021−2035). http://zfcj.gz.gov.cn/zwgk/xxgkml/bmwj/zcjd/content/post_8556574.html (accessed 15 Dec.2023).

GSB (Guangzhou Statistics Bureau), 2021. Guangzhou Statistical Yearbook 2021. Guangzhou Statistics Press, Guangzhou.

Guenther, A.B., Jiang, X., Heald, C.L., et al., 2012. The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions. Geosci. Model Dev. (GMD) 5, 1471−1492. https://doi.org/10.5194/gmd-5-1471-2012.

IEA (International Energy Agency), 2019. World Energy Outlook 2019.

Isik, M., Dodder, R., Kaplan, P.O., 2021. Transportation emissions scenarios for New York City under different carbon intensities of electricity and electric vehicle adoption rates. Nat. Energy 6, 92−104. https://doi.org/10.1038/s41560-020-00740-2.

Jerrett, M., Burnett, R.T., Pope, C.A., et al., 2009. Long-term ozone exposure and mortality. N. Engl. J. Med. 360, 1085−1095. https://doi.org/10.1056/NEJMoa0803894.

Jiang, J., Ye, B., Shao, S., et al., 2021. Two-tier synergic governance of greenhouse gas emissions and air pollution in China's megacity, Shenzhen: impact evaluation and policy implication. Environ. Sci. Technol. 55, 7225−7236. https://doi.org/10.1021/acs.est.0c06952.

Klimont, Z., Kupiainen, K., Heyes, C., et al., 2017. Global anthropogenic emissions of particulate matter including black carbon. Atmos. Chem. Phys. 17, 8681−8723. https://doi.org/10.5194/acp-17-8681-2017.

Lelieveld, J., Evans, J.S., Fnais, M., et al., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 525, 367−371. https://doi.org/10.1038/nature15371.

Li, K., Jacob, D.J., Liao, H., Shen, L., et al., 2019a. Anthropogenic drivers of 2013−2017 trends in summer surface ozone in China. Proc. Natl. Acad. Sci. 116, 422−427. https://doi.org/10.1073/pnas.1812168116.

Li, K., Jacob, D.J., Liao, H., Zhu, J., et al., 2019b. A two-pollutant strategy for improving ozone and particulate air quality in China. Nat. Geosci. 12, 906−910. https://doi.org/10.1038/s41561-019-0464-x.

Liu, J., Zheng, Y., Geng, G., et al., 2020. Decadal changes in anthropogenic source contribution of $PM_{2.5}$ pollution and related health impacts in China, 1990−2015. Atmos. Chem. Phys. 20, 7783−7799. https://doi.org/10.5194/acp-20-7783-2020.

Lu, C., Adger, W.N., Morrissey, K., et al., 2022. Scenarios of demographic distributional aspects of health co-benefits from decarbonising urban transport. Lancet Planet. Health 6, 461−474. https://doi.org/10.1016/S2542-5196(22)00089-4.

Lu, X., Hong, J., Zhang, L., et al., 2018. Severe surface ozone pollution in China: a global perspective. Environ. Sci. Technol. Lett. 5, 487−494.

Lu, X., Zhang, L., Wang, X., et al., 2020. Rapid increases in warm-season surface ozone and resulting health impact in China since 2013. Environ. Sci. Technol. Lett. 7, 240−247. https://doi.org/10.1021/acs.estlett.0c00171.

MEE (Ministry of Ecology and Environment of the People's Republic of China), 2022. Notice of Action Plan for Efforts to Eliminate Heavy Pollution Weather. Control Ozone Pollut Address Diesel Truck Pollut. https://www.mee.gov.cn/xxgk2018/xxgk/xxgk03/202211/t20221116_1005042.html.

Murray, C.J.L., Aravkin, A.Y., Zheng, P., et al., 2020. Global burden of 87 risk factors in 204 countries and territories, 1990−2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet 396, 1223−1249. https://doi.org/10.1016/S0140-6736(20)30752-2.

NBS (National Bureau of Statistics), 2021. China Energy Statistical Yearbook 2021. China Statistics Press, Beijing.

NDRC (National Development and Reform Commission), 2017. National Carbon Emission Trading Market Construction Programme for Electric Power Sector. https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/201712/t20171220_960930.html.

Pope, C.A., Burnett, R.T., Thun, M.J., et al., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. JAMA 287, 1132−1141. https://doi.org/10.1001/jama.287.9.1132.

Rafaj, P., Kiesewetter, G., Gül, T., et al., 2018. Outlook for clean air in the context of sustainable development goals. Glob. Environ. Change 53, 1−11. https://doi.org/10.1016/j.gloenvcha.2018.08.008.

Ramaswami, A., Tong, K., Fang, A., et al., 2017. Urban cross-sector actions for carbon mitigation with local health co-benefits in China. Nat. Clim. Change 7, 736−742. https://doi.org/10.1038/nclimate3373.

Stanaway, J.D., Afshin, A., Gakidou, E., et al., 2018. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990−2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 392, 1923−1994. https://doi.org/10.1016/S0140-6736(18)32225-6.

SEI (Stockholm Environment Institute), 2006. LEAP: Long Range Energy Alternative Planning System, User Guide for LEAP 2006. http://www.energycommunity.org/documents/Leap2006UserGuideEnglish.pdf.

Tang, R., Zhao, J., Liu, Y., et al., 2022. Air quality and health co-benefits of China's carbon dioxide emissions peaking before 2030. Nat. Commun. 13, 1008−1017. https://doi.org/10.1038/s41467-022-28672-3.

TPGGM (The People's Govermment o Guangzhou Municipality), 2016. 13th five-year plan of comprehensive transportation for Guangzhou. https://www.gz.gov.cn/zwgk/fggw/sfbgtwj/content.

TPGGM, 2017. Guangzhou's 13th Five-Year Plan for Energy Conservation and Carbon Reduction. https://www.gz.gov.cn.

TPGGM, 2020. Notice of the People's Government of Guangzhou Municipality on Printing and Distributing the Outline of the 14th Five-Year Plan (2021−2025) for National Economic and Social Development and Vision 2035 of Guangzhou City. https://www.gz.gov.cn/zwgk/fggw/szfwj/content/post_7288094.html (accessed 15 Dec 2023).

TPGGM, 2022a. Notice of the People's Government of Guangzhou Municipality on Printing and Distributing the "14th Five-Year Plan" for the Development of Industry and Information Technology of Guangzhou City. https://www.gz.gov.cn/zwgk/fggw/sfbgtwj/content/post_8319334.html (accessed Dec 15.2023).

TPGGM, 2022b. Notice of the People's Government of Guangzhou Municipality on Printing and Distributing the Integrated Development Plan for Transportation and Logistics of Guangzhou City. https://www.gz.gov.cn/zwgk/fggw/szfwj/content/post_7842597.html (accessed Dec 15.2023).

TPGGM, 2022c. Announcement on the "14th Five - Year Plan" for Guangzhou Municipal Ecological and Environmental Protection. https://www.gz.gov.cn/zwgk/fggw/wyzzc/content/post_8444943.html (accessed Dec 15.2023).

Tian, X., Dai, H., Geng, Y., et al., 2018. Economic impacts from $PM_{2.5}$ pollution-related health effects in China's road transport sector: a provincial-level analysis. Environ. Int. 115, 220−229. https://doi.org/10.1016/j.envint.2018.03.030.

Tong, D., Geng, G., Jiang, K., et al., 2019. Energy and emission pathways towards $PM_{2.5}$ air quality attainment in the Beijing−Tianjin−Hebei region by 2030. Sci. Total Environ. 692, 361−370. https://doi.org/10.1016/j.scitotenv.2019.07.218.

Tong, D., Geng, G., Zhang, Q., et al., 2021. Health co-benefits of climate change mitigation depend on strategic power plant retirements and pollution controls. Nat. Clim. Change 11, 1077−1083. https://doi.org/10.1038/s41558-021-01216-1.

Turner, M.C., Jerrett, M., Pope, C.A., et al., 2016. Long-term ozone exposure and mortality in a large prospective study. Am. J. Respir. Crit. Care Med. 193, 1134−1142. https://doi.org/10.1164/rccm.201508-1633OC.

Wang, X., Fu, T.-M., Zhang, Lin, et al., 2021. Sensitivities of ozone air pollution in the Beijing−Tianjin−Hebei area to local and upwind precursor emissions using adjoint modeling. Environ. Sci. Technol. 55, 5752−5762. https://doi.org/10.1021/acs.est.1c00131.

West, J.J., Smith, S.J., Silva, R.A., et al., 2013. Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. Nat. Clim. Change 3, 885−889. https://doi.org/10.1038/nclimate2009.

WHO (World Health Organization), 2023. WHO Ambient Air Quality Database, 2022 Update: Status Report.

Wu, P., Guo, F., Cai, B., et al., 2021. Co-benefits of peaking carbon dioxide emissions on air quality and health, a case of Guangzhou, China. J. Environ. Manag. 282, 111796−111805. https://doi.org/10.1016/j.jenvman.2020.111796.

Yu, M., Zhu, Y., Lin, C.-J., et al., 2019. Effects of air pollution control measures on air quality improvement in Guangzhou, China. J. Environ. Manag. 244, 127−137. https://doi.org/10.1016/j.jenvman.2019.05.046.

Zhang, L., Niu, M., Zhang, Z., et al., 2023. A new method of hotspot analysis on the management of CO_2 and air pollutants, a case study in Guangzhou city, China. Sci. Total Environ. 856, 159040. https://doi.org/10.1016/j.scitotenv.2022.159040.

Zhang, Q., Zheng, Y., Tong, D., et al., 2019. Drivers of improved $PM_{2.5}$ air quality in China from 2013 to 2017. Proc. Natl. Acad. Sci. U. S. A. 116, 24463−24469. https://doi.org/10.1073/pnas.1907956116.

Zhang, S., Wu, Y., Liu, X., et al., 2021. Co-benefits of deep carbon reduction on air quality and health improvement in Sichuan province of China. Environ. Res. Lett. 16, 95011−95021. https://doi.org/10.1088/1748-9326/ac1133.

Zheng, B., Tong, D., Li, M., et al., 2018. Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions. Atmos. Chem. Phys. 18, 14095−14111. https://doi.org/10.5194/acp-18-14095-2018.

Zheng, H., Zhao, B., Wang, S., et al., 2019. Transition in source contributions of $PM_{2.5}$ exposure and associated premature mortality in China during 2005-2015. Environ. Int. 132, 105111−105120. https://doi.org/10.1016/j.envint.2019.105111.