



# A systematic assessment of city-level climate change mitigation and air quality improvement in China



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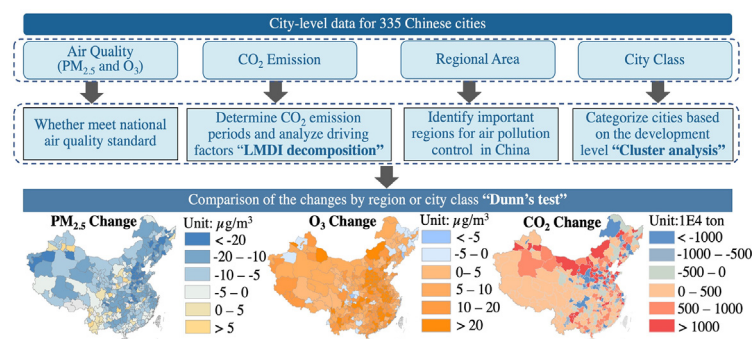
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## HIGHLIGHTS

- City-level trends in PM<sub>2.5</sub>, O<sub>3</sub>, and CO<sub>2</sub> were not consistent in China from 2015 to 2019.
- Air quality varied by region not city class; CO<sub>2</sub> emissions varied by city class not region.
- Mandatory city-level reduction targets were effective in reducing PM<sub>2.5</sub> concentrations.
- China should set mandatory city-level CO<sub>2</sub> emissions reduction targets based on development levels.

## GRAPHIC ABSTRACT



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## ABSTRACT

China is facing dual challenges of air pollution and climate change. By using city-level data, we comprehensively assessed air quality and CO<sub>2</sub> emission changes from 2015 to 2019 for 335 Chinese cities. We selected important regions for air pollution control and categorized all cities into different classes according to their development levels. Our novel approach revealed new insights on different patterns of changes of PM<sub>2.5</sub>, O<sub>3</sub>, and CO<sub>2</sub> by region and city class. We found that PM<sub>2.5</sub> concentrations decreased remarkably due to mandatory city-level reduction targets, especially in the Beijing-Tianjin-Hebei (−27%) region. Nonetheless, O<sub>3</sub> concentrations and CO<sub>2</sub> emissions increased in 91% and 69% of Chinese cities, respectively. Observed CO<sub>2</sub> emission reductions in more developed cities were mainly due to prominent energy intensity reduction and energy structure improvement. Our study indicates a lack of synergy in air pollution control and CO<sub>2</sub> mitigation under current policies in China. To address both challenges holistically, we

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suggest setting mandatory city-level CO<sub>2</sub> emission reduction targets and reinforcing clean energy and energy efficiency measures.

## 1. Introduction

With the fast industrialization and urbanization, China has become the world's largest carbon dioxide (CO<sub>2</sub>) emitter in 2005 (BP, 2021). CO<sub>2</sub> emissions from fossil fuel combustion and industrial processes account for roughly 92% of the total greenhouse gas (GHG) emissions in China (China Ministry of Ecology and Environment, 2018). In the meantime, fossil fuel combustion and industrial processes can also produce air pollutants (Lu et al., 2020; Oh et al., 2019), including PM<sub>2.5</sub> (particulate matter with an aerodynamic diameter  $\leq 2.5 \mu\text{m}$ ) and precursors of ozone (O<sub>3</sub>). Both PM<sub>2.5</sub> and O<sub>3</sub> have been shown to have adverse effects on human health (Bruneekreef and Holgate, 2002; Burnett et al., 2018). A considerable amount of effort had been made in the past decade to tackle air pollution in China (Zhang et al., 2019; Zheng et al., 2017). Yet, almost half of Chinese cities still failed to meet the national annual ambient air quality standard of 35  $\mu\text{g}/\text{m}^3$  for PM<sub>2.5</sub> in 2019 (China National Environmental Monitoring Centre, 2021). In addition, severe O<sub>3</sub> pollution, especially in the summer-time, has been observed in China in recent years (K. Li et al., 2019a, 2019b; Xing et al., 2019).

To reduce CO<sub>2</sub> emissions and improve air quality, China had set specific goals and mitigation policies. For CO<sub>2</sub> mitigation, China claimed to implement more aggressive actions against climate change by reaching the CO<sub>2</sub> emission peak before 2030 and carbon neutrality by 2060 in the Climate Ambition Summit (Climate Ambition Summit, 2020). On the other hand, China had introduced strict clean air policies since 2013 to control air pollution (State Council of the People's Republic of China, 2018, 2013). The 2035 “Beautiful China” target was also proposed to require most cities in China to achieve the annual PM<sub>2.5</sub> standard ( $<35 \mu\text{g}/\text{m}^3$ ) by 2035 (Xinhua, 2020). These efforts had resulted in marked improvements in ambient air quality in China (Cai et al., 2017; Zhang et al., 2019), including a 33% reduction in PM<sub>2.5</sub> concentrations between 2013 and 2017 (Huang et al., 2017).

Previous studies have shown that control measures reducing CO<sub>2</sub> emissions could also reduce air pollution and vice versa, as many air pollutants and CO<sub>2</sub> were emitted from the same sources, such as fossil fuel burning (Lu et al., 2020; Oh et al., 2019). Therefore, well-designed mitigation policies could potentially reduce CO<sub>2</sub> emissions (Jiang et al., 2013; Lu et al., 2019) and improve air quality (N. Li et al., 2019d; Markandya et al., 2009; Nemet et al., 2010; West et al., 2013) simultaneously. However, previous studies that evaluated the air quality improvement or CO<sub>2</sub> emission reductions in China often treated them as two separate issues. Further, those studies were usually conducted at the regional or national levels (Cai et al., 2017; Zhang et al., 2019), with only a few studies focusing on the cities (Jiang et al., 2021; Wang et al., 2019). As a result, a comprehensive evaluation at the city-level resolution that quantifies the changes for both air quality and CO<sub>2</sub> emissions is still missing, which hinders China from achieving its goal on both climate mitigation and air pollution control.

In this study, we assessed the changes of CO<sub>2</sub> emissions and air quality for 335 Chinese cities from 2015 to 2019. We selected important regions for air pollution control, categorized all cities into different classes according to their development levels, and emphasized the differences observed among different pollutants and CO<sub>2</sub> emissions for different regions and city classes. Our results could provide insights for future policies to meet both climate and air quality control targets in China.

## 2. Material and methods

### 2.1. Data

CO<sub>2</sub> emission data for all cities in China were compiled by the China City Greenhouse (CCG) working group (CCG, 2020) and sourced from

China High Resolution Emission Database (CHRED) 3.0 database (Cai et al., 2019a, 2019b, 2018; CHRED, 2020). CCG working group was a voluntary organization with 137 researchers from 76 institutes dedicated to building the fundamental GHG data for cities in China (Cai et al., 2019a). CHRED 3.0 database was compiled by utilizing bottom-up, enterprise-level point sources with high quality and accuracy, including point sources and gridded emission data. CCG working group verified and cross-checked the CHRED 3.0 database with data in open statistical yearbooks, official reports, personal surveys, and field investigations, and finally established the CO<sub>2</sub> emission data for cities in China (Cai et al., 2019a).

Air quality data were sourced from the China National Environmental Monitoring Centre (China National Environmental Monitoring Centre, 2021). In China, O<sub>3</sub> concentrations were reported in mass concentration (unit:  $\mu\text{g}/\text{m}^3$ ) at a reference meteorological condition with an ambient temperature of 298 K and pressure of 1013 hPa. To facilitate the comparison with reported O<sub>3</sub> concentrations in most countries (unit: ppb), we thus converted the collected O<sub>3</sub> concentrations with the coefficient of 1.95  $\mu\text{g}/\text{m}^3$  to 1 ppb. The national O<sub>3</sub> standard of 160  $\mu\text{g}/\text{m}^3$  (the 90th percentile of daily 8-h maximum concentrations) was converted to 82 ppb accordingly. The exact data are shown in Supplementary Table S1.

Gross Domestic Product (GDP), permanent population, and industrial structure data from 2015 to 2019 were obtained from the Statistical Bulletin on the National Economic and Social Development for each city (National Bureau of Statistics, 2020a) and the statistical yearbook for each province or city (National Bureau of Statistics, 2020b). To exclude inflation and other price increases, GDP was converted to constant numbers in 2015.

### 2.2. Identification of the periods of CO<sub>2</sub> emissions

To determine the different periods of CO<sub>2</sub> emissions, we first identified the maximum CO<sub>2</sub> emission data for each city from 2005 to 2019 as the “peak value”. Then, we used the Mann-Kendall Trend test to analyze changes of CO<sub>2</sub> emissions after the “peak value” year. Finally, based on the test results, we assign each city into one of the three periods of decline, plateau, and growth, respectively (Supplementary Figs. S1–S3) (Jiang et al., 2021). Specifically, the period of growth was defined when the CO<sub>2</sub> emission was increasing continuously from 2005 to 2019. The period of plateau was defined when the CO<sub>2</sub> emission was around the maximum emission level in recent years. The period of decline was defined when the CO<sub>2</sub> emission showed a marked decreasing trend after reaching the maximum emission level.

### 2.3. K-means clustering analysis for city classes

To better understand the characteristics of Chinese cities, all 335 cities were grouped into five classes using the k-means cluster analysis based on the attribute characteristics, including the GDP, permanent population, and proportion of secondary industry and tertiary industry (Hartigan and Wong, 1979). K-means clustering is a vector quantization method. It searches for a pre-determined number of clusters in an unlabeled dataset, where each observation belongs to the nearest mean. The process includes (1) pre-dividing the dataset into  $k$  groups, (2) randomly selecting  $k$  objects as the cluster centers, (3) calculating the distance between each object and each cluster center, and (4) assigning each object to the nearest cluster center. The distance is calculated by the following equations:

$$\mu_i = \frac{1}{|C_i|} \sum_{x \in C_i} x \quad (1)$$

$$E = \sum_{i=1}^k \sum_{x \in C_i} |x - \mu_i|^2 \quad (2)$$

where  $\mu_i$  represents the mean value of cluster  $C_i$ ,  $x$  represents the selected attribute characteristics of every unit,  $i$  represents the cluster number,  $\in$  represents belongs to,  $E$  represents the sum of squared errors within the cluster, which is usually adopted as the standard measure function. By calculating the distance between each object and each cluster center for the different number of clusters, we finally selected five clusters as the optimal  $k$ , as shown in Supplementary Fig. S4. The summary of characteristics for cities Classes 1–5 is shown in Supplementary Table S2.

#### 2.4. Dunn's test

Dunn's test (Dunn, 1964) was used to compare the changes of air pollutant concentrations (PM<sub>2.5</sub> and O<sub>3</sub>) and CO<sub>2</sub> emissions among different regions or different city classes. We first used the Shapiro–Wilk normality test to check the normality of the data (Royston, 1982) (Supplementary Table S3). Then, based on the normality results, Dunn's test was used to compare the changes among multiple pairwise groups. The groups included important regions for air pollution control, including Beijing–Tianjin–Hebei and the surrounding region (BTH & the 2 + 26 cities), the Yangtze River Delta region (YRD), the Pearl River Delta region (PRD), the Fenwei Plain region (FWP), and the Cheng–Yu District region (CYD) (Supplementary Table S4). The groups also included different city classes (Classes 1 to 5) (Supplementary Table S5). Shapiro test and Dunn test functions of the R 3.6.3 version were applied to perform the statistical tests. The significance level was set at  $p < 0.05$ .

#### 2.5. Logarithmic mean Divisia index decomposition analysis

To understand the driving forces of changes of CO<sub>2</sub> emissions, we used the logarithmic mean Divisia index (LMDI) that decomposed the CO<sub>2</sub> emissions into factors of population, GDP per capita, energy intensity, and energy structure (Ang, 2005) as follows:

$$C = \sum_j \frac{C_j}{E_j} \times \frac{E_j}{E} \times \frac{E}{GDP} \times \frac{GDP}{P} \times P = \sum_j U_j \times M_j \times I \times GP \times P \quad (3)$$

$$\Delta C = C^t - C^{t-1} = \Delta U + \Delta M + \Delta I + \Delta GP + \Delta P \quad (4)$$

$$\Delta U = \sum_j \frac{C_j^t - C_j^{t-1}}{\ln C_j^t - \ln C_j^{t-1}} \ln \frac{U_j^t}{U_j^{t-1}} \quad (5)$$

$$\Delta M = \sum_j \frac{C_j^t - C_j^{t-1}}{\ln C_j^t - \ln C_j^{t-1}} \ln \frac{M_j^t}{M_j^{t-1}} \quad (6)$$

$$\Delta I = \sum_j \frac{C_j^t - C_j^{t-1}}{\ln C_j^t - \ln C_j^{t-1}} \ln \frac{I^t}{I^{t-1}} \quad (7)$$

$$\Delta GP = \sum_j \frac{C_j^t - C_j^{t-1}}{\ln C_j^t - \ln C_j^{t-1}} \ln \frac{GP^t}{GP^{t-1}} \quad (8)$$

$$\Delta P = \sum_j \frac{C_j^t - C_j^{t-1}}{\ln C_j^t - \ln C_j^{t-1}} \ln \frac{P^t}{P^{t-1}} \quad (9)$$

where  $C$  represents the CO<sub>2</sub> emission,  $E$  represents the energy consumption,  $GDP$  represents the city-level GDP,  $P$  represents the permanent population,  $j$  represents the fuel type,  $U$  represents the CO<sub>2</sub> emission factor,  $M$  represents the fuel mix,  $I$  represents the energy intensity,  $GP$  represents the GDP per capita,  $t$  and  $t - 1$  represents the year 2019 and 2015.

### 3. Results

#### 3.1. Changes in air quality and CO<sub>2</sub> emissions from 2015 to 2019

Fig. 1 shows the percent changes of air pollutant concentrations (PM<sub>2.5</sub> and O<sub>3</sub>) and CO<sub>2</sub> emissions from 2015 to 2019 for 335 cities in China. City-level PM<sub>2.5</sub>, O<sub>3</sub>, and CO<sub>2</sub> data in 2015 and 2019 can be found in Supplementary Table S1. In Fig. 1A–1B, the blue color represents cities that had met China's national air quality standard of the corresponding air pollutants in 2019; and the orange color represents those that had not. In Fig. 1C, green, purple, and grey colors represent different CO<sub>2</sub> emission states of the cities (i.e., the periods of decline, plateau, and growth), respectively. Among the analyzed pollutants, PM<sub>2.5</sub> concentration decreased in 88% ( $N = 295$ ) of the 335 cities with an average reduction of 23% in 2019 compared to 2015 (Fig. 1A). Nonetheless, almost half (47%,  $N = 158$ ) of the cities still failed to meet China's national PM<sub>2.5</sub> standard (i.e., an annual average of 35  $\mu\text{g}/\text{m}^3$ ) by 2019 (Fig. 1A), which was much looser compared to the 5  $\mu\text{g}/\text{m}^3$  standard by the World Health Organization (WHO) (World Health Organization, 2021). In contrast, as presented in Fig. 1B, O<sub>3</sub> concentration increased in 304 (91%) Chinese cities and 103 (31%) of them failed to meet the national O<sub>3</sub> standard (82 ppb). For CO<sub>2</sub>, 231 cities had increased emissions from 2015 to 2019, and 56 cities showed over 50% increase during this period (Fig. 1C). Among all 335 cities, only 20% ( $N = 67$ ) were in the period of decline or plateau of CO<sub>2</sub> emissions.

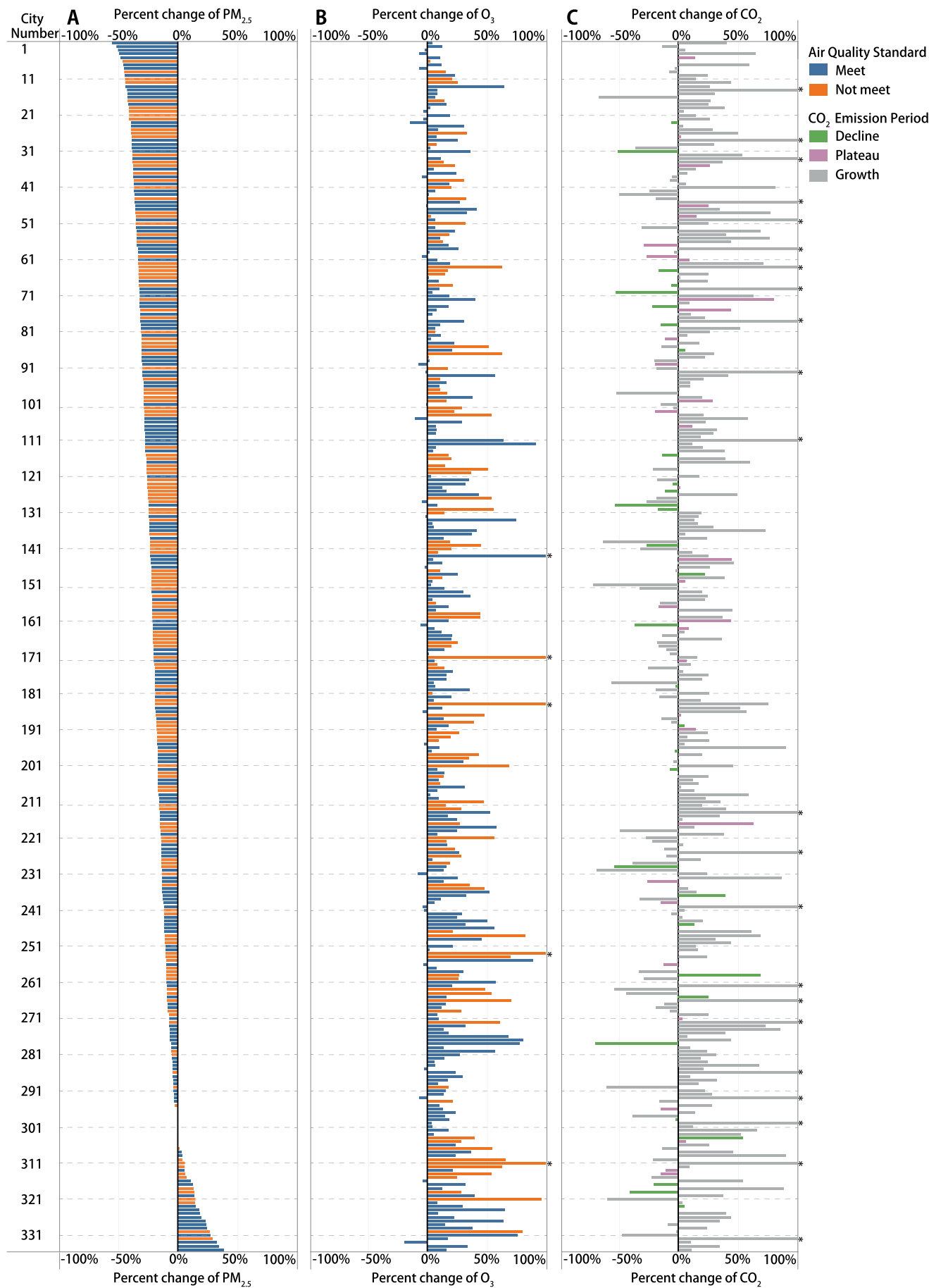
By comparing the changes of PM<sub>2.5</sub> and CO<sub>2</sub>, we found that 27% of the cities ( $N = 90$ ) had reduced both (co-reduction) in 2019 compared to 2015, with an average reduction of 23% for PM<sub>2.5</sub> and 22% for CO<sub>2</sub> emissions, respectively (Fig. 1A). For the remaining 73% of the cities ( $N = 245$ ), CO<sub>2</sub> emissions increased by an average of 33%, while PM<sub>2.5</sub> concentration decreased by an average of 18%. Overall, our results showed a lack of synchronized city-level co-reduction of CO<sub>2</sub> and PM<sub>2.5</sub> under current climate change and air pollution control policies in China.

#### 3.2. Spatial pattern of air quality and CO<sub>2</sub> emission changes

Fig. 2 presents the spatial distribution of air quality and CO<sub>2</sub> emissions for the 335 cities in China. In Fig. 2A–B and D–E, non-attainment cities for PM<sub>2.5</sub> and O<sub>3</sub> were shown in pink dots. The black, brown, rose red, red, and blue polygons represent the BTH, YRD, PRD, FWP, and CYD regions, respectively, which are important regions for air pollution control in China (Fig. 2C and F). The green check mark and the purple triangle represent the cities in the period of decline or plateau of CO<sub>2</sub> emissions, and the rest of the cities are in the period of growth of CO<sub>2</sub> emissions (Fig. 2I).

As shown in Fig. 2A–C, only 106 Chinese cities had met the national PM<sub>2.5</sub> standard in 2015, which were mainly located in the southern (Fujian and Guangdong provinces) and southwest (Yunnan province) areas of China. In 2019, 72 additional cities had met the PM<sub>2.5</sub> standard due to effective control measures on sulfur dioxide (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), and other precursors of PM<sub>2.5</sub>, which were mainly located in the northeastern (Heilongjiang, Jilin province, and Inner Mongolia Autonomous Region), western (Gansu province), central (Sichuan province), and southern (Guangdong and Guangxi province) areas. Although a noticeable PM<sub>2.5</sub> reduction was observed in the BTH region ( $-27 \mu\text{g}/\text{m}^3$ ) (Fig. 2C), none of the cities in this region had met the national PM<sub>2.5</sub> standard in 2019 (Fig. 2B). Similarly, none of the cities in the FWP region had met the PM<sub>2.5</sub> standard in 2019. Besides, only 27% and 31% of the cities in the YRD and CYD regions had met the standard in 2019. In comparison, all cities in the PRD region had met the national standard in 2019.

As shown in Fig. 2D–F, the average national O<sub>3</sub> concentration increased rapidly from 63 ppb in 2015 to 76 ppb in 2019. From 2015 to 2019, the most prominent increase in O<sub>3</sub> (absolute concentration change) was observed in the FWP and BTH regions (+12 ppb), followed by the PRD (+10 ppb), YRD (+8 ppb), and CYD (+4 ppb) regions, respectively (Fig. 2F). The number of non-attainment cities for O<sub>3</sub> increased by more than five times from 2015 (19 cities) to 2019 (103 cities), with half of the



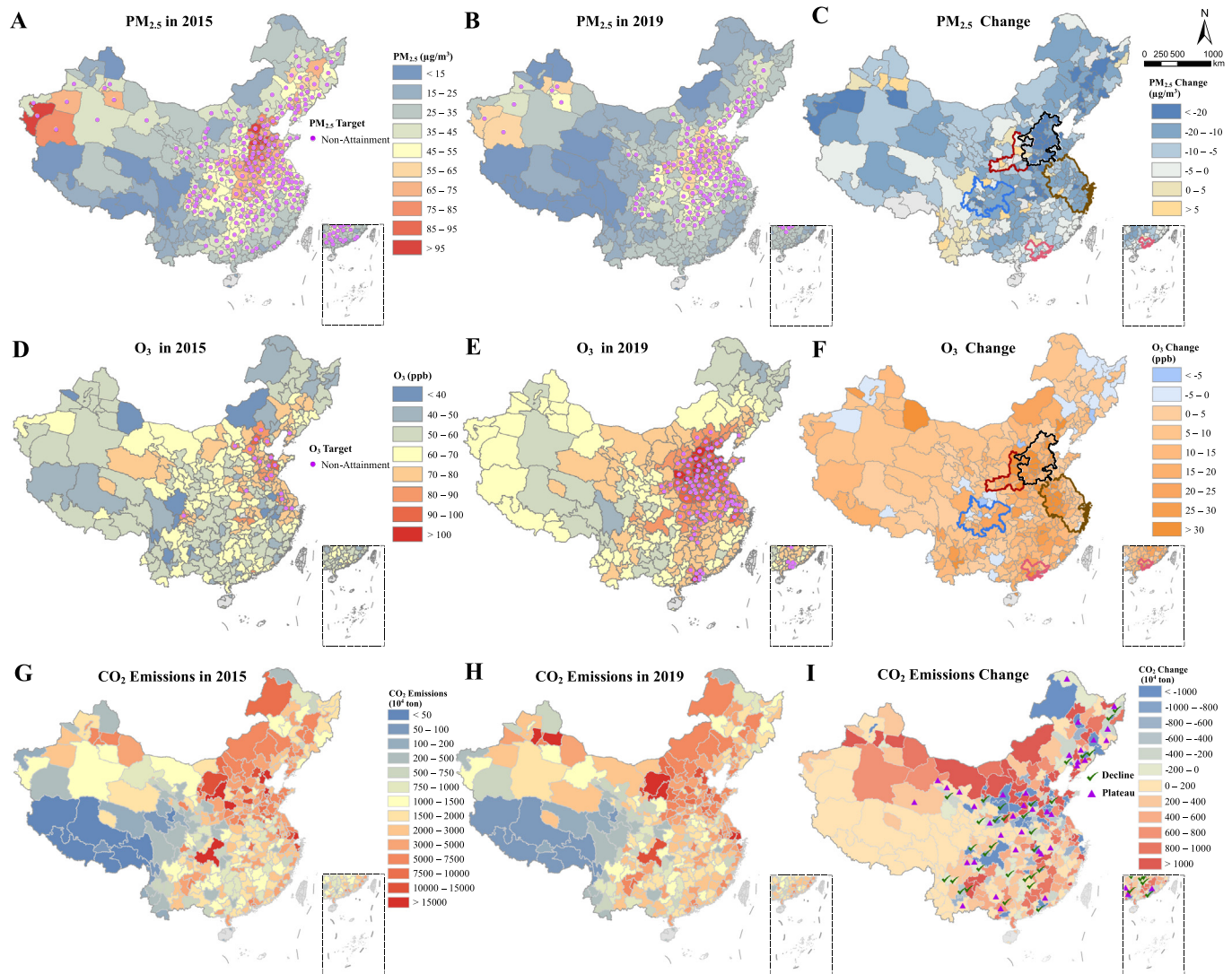


**Fig. 2.** The spatial pattern of  $\text{PM}_{2.5}$ ,  $\text{O}_3$ , and  $\text{CO}_2$  for 335 cities in China from 2015 to 2019. (A)  $\text{PM}_{2.5}$  in 2015; (B)  $\text{PM}_{2.5}$  in 2019; (C) Changes of  $\text{PM}_{2.5}$  concentrations from 2015 to 2019; (D)  $\text{O}_3$  in 2015; (E)  $\text{O}_3$  in 2019; (F) Changes of  $\text{O}_3$  concentrations from 2015 to 2019. The pink dots in (A) and (B) represent the cities not meeting the national  $\text{PM}_{2.5}$  standard ( $35 \mu\text{g}/\text{m}^3$ ) in 2015 or 2019. The pink dots in (D) and (E) represent the cities not meeting the national  $\text{O}_3$  standard (82 ppb) in 2015 or 2019. The black, brown, rose red, red, and blue polygons in (C) and (F) represent BTH - the Beijing-Tianjin-Hebei and the surrounding region, YRD - the Yangtze River Delta region, PRD - the Pearl River Delta region, FWP - the Fenwei Plain region, and CYD - the Cheng-Yu District region, respectively. (G)  $\text{CO}_2$  emissions in 2015; (H)  $\text{CO}_2$  emissions in 2019; (I) Changes of  $\text{CO}_2$  emissions from 2015 to 2019. The green check mark and the purple triangle in (I) represent the cities in the period of decline and plateau of  $\text{CO}_2$  emissions, respectively. The rest of the cities are in the period of growth of  $\text{CO}_2$  emissions.

additional non-attainment cities located in the BTH, YRD, PRD, and FWP regions. In 2019, 100%, 61%, 78%, and 82% of the cities in the BTH ( $N = 28$ ), PRD ( $N = 7$ ), YRD ( $N = 25$ ), and FWP ( $N = 9$ ) regions exceeded the national  $\text{O}_3$  standard, and 61% of the cities in the BTH region ( $N = 17$ ) exceeded the standard by over 20%. Our results clearly showed that the  $\text{O}_3$  pollution worsened from 2015 to 2019 in China. This is likely due to the fact that China's current air pollution prevention and control action plan has effective control measures on  $\text{NO}_x$  emissions, but not on volatile organic compounds (VOCs) (M. Li et al., 2019c).  $\text{NO}_x$  reduction would increase  $\text{O}_3$  under the current VOC-limited conditions in urban areas of China (K. Li et al., 2019a). This finding was also supported by satellite observations of the formaldehyde to  $\text{NO}_2$  ratio as the indicator of  $\text{O}_3$ - $\text{NO}_x$

VOC sensitivity (Wang et al., 2021). Besides,  $\text{PM}_{2.5}$  reductions could weaken aerosol uptake of hydroperoxy radicals which also contributes to more  $\text{O}_3$  production (K. Li et al., 2019a).  $\text{PM}_{2.5}$  reductions also improve visibility, which promote the photochemical reaction and  $\text{O}_3$  formation (Yang et al., 2020). Thus, in the future, China should implement both  $\text{NO}_x$  and VOC emission control measures to address  $\text{O}_3$  pollution (K. Li et al., 2019b).

For  $\text{CO}_2$  (Fig. 2G–H), cities with high emissions were mainly located in the northern (Hebei and Shandong provinces) and northeastern (Inner Mongolia Autonomous Region) areas, while cities with lower emissions were mainly located in the southwestern (Tibet and Yunnan provinces) areas. The amount of national  $\text{CO}_2$  emissions increased from 9334 Mt. (Million ton) in 2015 to 9890 Mt. in 2019. An increase of more than

**Fig. 1.** Percent change of air pollutant concentrations and  $\text{CO}_2$  emissions from 2015 to 2019 for 335 cities in China. (A)  $\text{PM}_{2.5}$ ; (B)  $\text{O}_3$ ; (C)  $\text{CO}_2$ . Panels A – B: The blue color - cities met the air quality standard in 2019; the orange color - cities did not meet the air quality standard in 2019. The national standards of  $\text{PM}_{2.5}$  and  $\text{O}_3$  are  $35 \mu\text{g}/\text{m}^3$  and 82 ppb, respectively. Panel C: The green, purple, and grey color - cities are in the period of decline, plateau, and growth of  $\text{CO}_2$  emissions. Note that percent change shows the range from  $-100\%$  to  $100\%$  and values exceeding  $100\%$  are marked with symbol \* in this figure.

10 Mt. was observed in 42 cities, which were mainly located in Hebei, Inner Mongolia, Shandong, and Shanxi provinces (Fig. 2I). Based on our analysis, only 31 cities had reached a period of decline of CO<sub>2</sub> emissions and 36 cities had reached the plateau by 2019 (Fig. 2I). These cities together contributed to 17% of the national CO<sub>2</sub> emissions in 2019. All other cities ( $N = 268$ ) were still in the period of growth and contributed to 83% of CO<sub>2</sub> emissions in China.

### 3.3. Regional differences of changes in air quality and CO<sub>2</sub> emissions

Fig. 3A–C showed the changes of air pollutant concentrations and CO<sub>2</sub> emissions by region, including BTH, CYD, YRD, PRD, FWP, and other regions, from 2015 to 2019.

Among all regions, the BTH region had the most prominent decrease in PM<sub>2.5</sub> (−27%) (Fig. 3A) since the most stringent requirements and control strategies were implemented there (State Council of the People's Republic of China, 2018; Zhang et al., 2019). In comparison, PRD and FWP showed less decrease in PM<sub>2.5</sub> (−11% and −2%, respectively) than BTH (Supplementary Table S4). In contrast, O<sub>3</sub> concentrations increased across all regions. As shown in Fig. 3B, the most dramatic O<sub>3</sub> increase was observed in the FWP region (+42%), followed by BTH (+39%), YRD (+36%), PRD (+33%), CYD (+18%), and other region (+18%). Different from air pollutant concentrations, CO<sub>2</sub> emissions showed less differences across different regions except for the FWP region, where a decrease of 4% was observed. For other regions, the CO<sub>2</sub> emission increase was in the range of 8% to 21% (Fig. 3C).

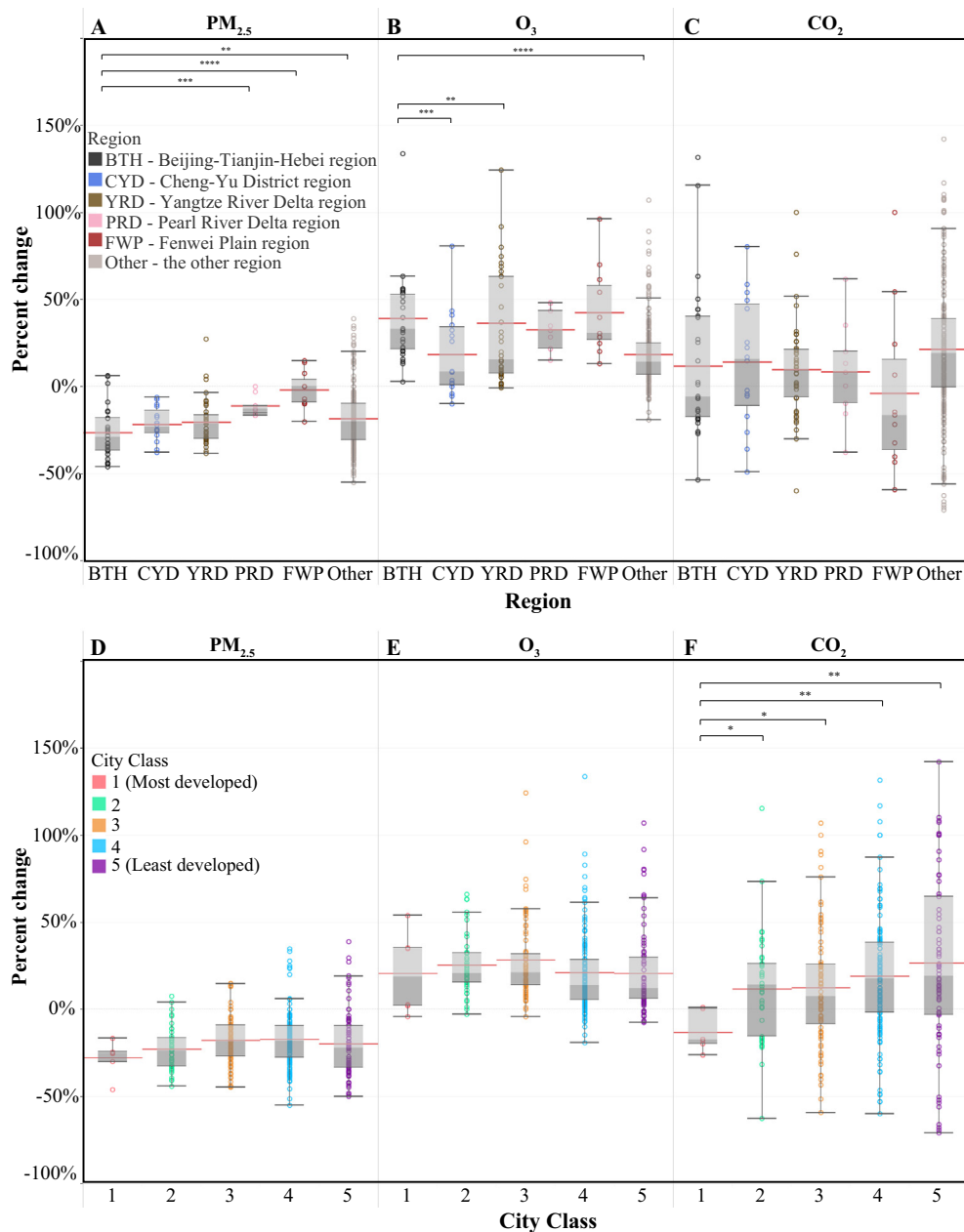


**Fig. 3.** Comparison of percent changes of air pollutant concentrations and CO<sub>2</sub> emissions for different regions (A–C) and classes of cities (D–F) in China from 2015 to 2019. (A, D) PM<sub>2.5</sub>; (B, E) O<sub>3</sub>; and (C, F) CO<sub>2</sub> emissions. Regions included BTH - Beijing-Tianjin-Hebei region and the surrounding region, PRD - Pearl River Delta region, YRD - Yangtze River Delta region, FWP - Fenwei Plain region, CYD - Cheng-Yu District region, and other region - the remaining cities. City Classes 1–5 represent the cities identified by the cluster analysis (see Method for details). Dunn's test significance level \*:  $p \leq 0.05$ ; \*\*:  $p \leq 0.01$ ; \*\*\*:  $p \leq 0.001$ ; \*\*\*\*:  $p \leq 0.0001$ . The solid red horizontal line represents the mean, the grey horizontal line represents the median, and the box represents the 25th to 75th percentiles.

Fig. 3D–F showed the changes of air pollutant concentrations and CO<sub>2</sub> emissions by city class, including Class 1–5 cities (representing the cities' development level), from 2015 to 2019. Different CO<sub>2</sub> emission characteristics were observed for different city classes. Class 1 cities ( $N = 6$ ) with the highest GDP per capita (average value of 12E4 RMB, Supplementary Table S2) had higher CO<sub>2</sub> emissions, with an average of 111 Mt. in 2019. Nevertheless, cities in Class 1 on average are the only ones showing a reduction of CO<sub>2</sub> emissions from 2015 to 2019. Cities in the other four classes are still experiencing an overall increase in CO<sub>2</sub> emissions (Fig. 3F). Class 2 ( $N = 42$ ) and Class 3 ( $N = 84$ ) cities were characterized by higher-than-average development level across the nation, with average GDP per capita of 8E4 RMB and 6E4 RMB, respectively (Supplementary Table S2). These two classes together contributed to half of the total CO<sub>2</sub> emissions in China, with average CO<sub>2</sub> emissions of 55 Mt. (Class 2) and 32 Mt. (Class 3) in 2019, and the same average change rate of +12% from 2015 to 2019 (Fig. 3F). Our results showed that only 18% of the cities in Classes 2 & 3 were in the period of decline or plateau, such as Shenzhen. In comparison, for Classes 4 & 5 cities, the amount of CO<sub>2</sub> emissions was relatively low, with an average of 28 Mt. and 16 Mt. in 2019, respectively. Cities in these classes were less developed and mainly located in the central and western parts of China. However, increasing trends in CO<sub>2</sub> emissions were found for these cities. There were 48% ( $N = 23$ ) and 50% ( $N = 39$ ) of the cities in Classes 4 & 5 showing CO<sub>2</sub> emission increases over 20% from 2015 to 2019 (Supplementary Table S1). Despite relatively low total CO<sub>2</sub> emissions, Classes 4 & 5 cities had much higher per capita CO<sub>2</sub> emissions of 10 tons and 18 tons, respectively, compared to cities in Classes 1–3 (around 6 tons) (Supplementary Table S2). Thus, special attention should be paid to the cities in Classes 4 & 5 as the economic development might further increase their CO<sub>2</sub> emissions substantially.

In contrast to the significant differences of CO<sub>2</sub> emissions across different city classes, the differences in air pollutant concentration changes, including PM<sub>2.5</sub> and O<sub>3</sub>, were less noticeable (Fig. 3D–E, Supplementary Table S5). From 2015 to 2019, the average PM<sub>2.5</sub> decreased by 17–28% for cities in different classes. In contrast, average O<sub>3</sub> concentrations increased by 21–28% from 2015 to 2019.

We then used the LMDI analysis to investigate the driving forces of CO<sub>2</sub> emission changes. As shown in Fig. 4, the reduction in energy intensity was the most important factor for CO<sub>2</sub> emission reduction, while the increase in GDP per capita was the driving factor for CO<sub>2</sub> emission increase. The effect of energy intensity was the most prominent in Class 1 cities (around –33%), followed by Classes 2–3 (around –15%) and Classes 4–5 cities (around –7%) (Fig. 4E–H). Besides, the effect of improved energy structure on CO<sub>2</sub> reduction was most obvious in Class 1 cities (–5%) compared to other city classes, but to a less extent than energy intensity. In addition, GDP per capita was the main positive driving force, leading to over 20% CO<sub>2</sub> emission increase for all city classes. We also compared the driving forces of CO<sub>2</sub> emission change by region (Fig. 4A–D). The reduced CO<sub>2</sub> emissions in the FWP region were mainly driven by the energy intensity factor (–22%) due to the strict control on coal consumption (Ministry of Ecology and Environment of the People's Republic of China, 2018).

#### 4. Discussion

China is facing both challenges of climate change and air pollution. Our study presented one of the first attempts to assess city-level air quality improvements and CO<sub>2</sub> emission reductions simultaneously, using data from 335 Chinese cities in 2015 and 2019. We compared the changes of PM<sub>2.5</sub> and O<sub>3</sub> concentrations and CO<sub>2</sub> emissions in parallel, which allowed us to realize the unsynchronized reduction trends under the current policies. Our results showed a 22% reduction of PM<sub>2.5</sub>, 21% increase of O<sub>3</sub>, and 6% increase of CO<sub>2</sub> emissions across 335 Chinese cities from 2015 to 2019.

The changes in air pollutant concentrations had distinct patterns across different regions, as air pollutant concentrations were affected by local emissions (Ge et al., 2018), regional transport from surrounding areas

(Chang et al., 2019), and meteorology conditions (L. Chen et al., 2020b). In China, pollution control policies were implemented based on regional joint prevention and control (Ministry of Ecology and Environment of the People's Republic of China, 2017; State Council of the People's Republic of China, 2018, 2013). Cities and their surrounding areas within the same region often set mandatory reduction goals with the uniform stringency level, which improved the effectiveness of pollution control. In the past several years, control policies accentuated the importance of PM<sub>2.5</sub> in particular by targeting PM<sub>2.5</sub> control at the city level. Policies were implemented mainly through end-of-pipe controls (Geng et al., 2021), which were driven by the strengthened emission standards (Zhang et al., 2019).

In contrast, CO<sub>2</sub> emission changes varied substantially among different city classes at different development stages. Our results showed that CO<sub>2</sub> emissions were driven by city's energy intensity, economic level, and energy structure, indicating a weak association with the geographical pattern. Energy intensity was the most dominant driving force of CO<sub>2</sub> emission compared with other factors. The reduction in energy intensity was more obvious in developed cities, suggesting a boosting economic development that utilized the energy more efficiently (Martínez et al., 2019). Developed cities represented the service-oriented cities in China with an average of 61.2% and 68.4% for the proportion of secondary tertiary industry in 2015 and 2019, respectively. Their economic structures had transitioned from emission-intensive industries to service types with less coal consumption. However, for less developed cities in China, CO<sub>2</sub> emissions increased rapidly due to economic development and less improvement in energy intensity. Thus, future low-carbon policies should prioritize the promotion on improving energy intensity and energy structure for less developed cities (Xing et al., 2020; Zhang et al., 2019). For example, for cities that still focus on manufacturing activities, they could adjust their industrial structures and improve energy efficiency, especially for carbon-intensive industries. Measures including promoting low-carbon technologies, adjusting the production structure to increase electric arc furnace steelmaking (for the iron and steel industry) (An et al., 2018; Ren et al., 2021), and clinker substitution (for the cement industry) (Xu et al., 2014) could be taken to reduce CO<sub>2</sub> emissions. The manufacturing-oriented cities could also improve their energy structure to prioritize the development of non-fossil fuel energy, especially in the electricity and power sector, which is also required by China's current low-carbon policy (State Council of the People's Republic of China, 2021). In addition, manufacturing-oriented cities could focus on high value-added products and increase the proportion of tertiary industry in their economic structure to reduce carbon-intensive manufacturing activities.

Currently, CO<sub>2</sub> mitigations were self-motivated at the city level, such as the “China's pilot low-carbon city” initiative (National Development and Reform Commission, 2010). However, our results found limited effectiveness of the initiative, as the statistical *t*-test did not show a significant difference in CO<sub>2</sub> emission changes between pilot low-carbon cities and non-pilot cities (Supplementary Fig. S5). To achieve the goal of CO<sub>2</sub> emission peak before 2030 and carbon neutrality by 2060 (Climate Ambition Summit, 2020), China should consider deriving future CO<sub>2</sub> mitigation policies from its own success in PM<sub>2.5</sub> control, such as setting mandatory city-level emission reduction targets as cities are the fundamental units to implement various policies in China (H. Chen et al., 2020a). Setting mandatory CO<sub>2</sub> mitigation targets for cities also fits the scope of China's future strategic positioning (State Council of the People's Republic of China, 2022).

Although great improvement was achieved for PM<sub>2.5</sub>, city-level co-reduction of CO<sub>2</sub> and PM<sub>2.5</sub> was not observed under the current policies. Only 29 cities met the national PM<sub>2.5</sub> standard and reached the period of plateau or decline of CO<sub>2</sub> emissions. The remaining cities faced either air pollution, or increasing CO<sub>2</sub> emission problem, or both. Current policies used strict end-of-pipe controls, which reduced air pollutant emissions effectively (Geng et al., 2021). For example, the implementation of the ultra-low emission standard could reach a 98% removal efficiency for PM<sub>2.5</sub> in the power sector (Zheng et al., 2018). However, the end-of-pipe control measure could increase CO<sub>2</sub> emissions due to increased energy

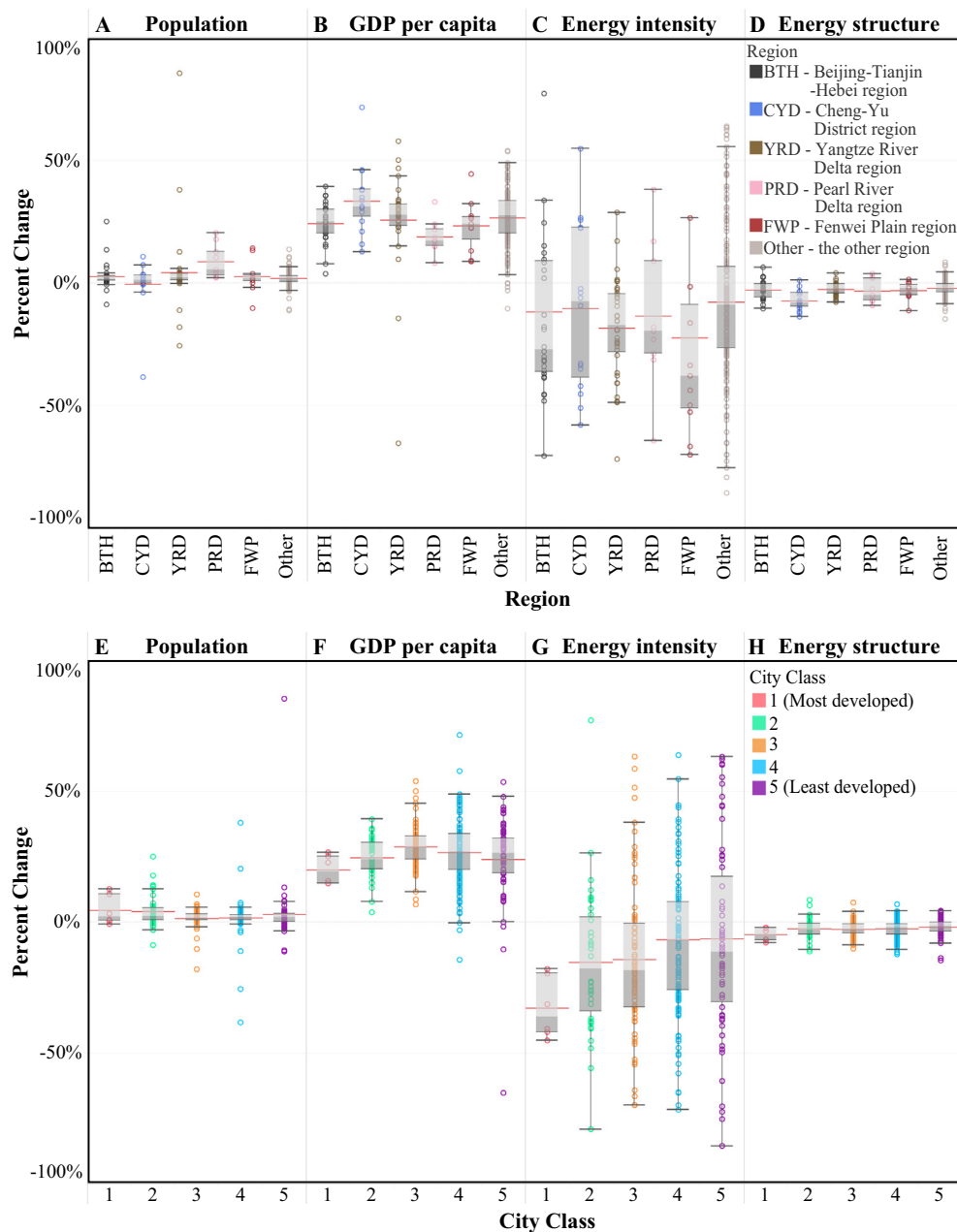


**Fig. 4.** The logarithmic mean Divisia index (LMDI) decomposition factors of (A, E) Population, (B, F) GDP per capita, (C, G) Energy intensity, and (D, H) Energy structure to the changes of CO<sub>2</sub> emissions for different regions (A – D) and city classes (E – H) in China from 2015 to 2019. Regions included BTH - the Beijing-Tianjin-Hebei and surrounding region, PRD - Pearl River Delta region, YRD - Yangtze River Delta region, FWP - Fenwei Plain region, CYD - Cheng-Yu District region, and other region - the remaining cities. City Classes 1–5 represent the cities identified by the cluster analysis (see Method for the detail). The solid red horizontal line represents the mean, the grey horizontal line represents the median, and the box represents the 25th to 75th percentiles.

consumption (Zhao et al., 2017). As the implementation of the advanced end-of-pipe control devices in major sectors increases, the future reduction potential decreases accordingly and their effectiveness on air quality improvements is decreasing (Geng et al., 2021; Xing et al., 2020). Considering the above, the implementation of low-carbon policies, such as clean energy transition and industrial structure optimization, is urgently needed as they could bring co-benefits of improving air quality and reducing CO<sub>2</sub> emissions (Wang et al., 2015; Xing et al., 2020). Existing energy policies that have the potential to effectively address both challenges in the long run should be reinforced in the further (Geng et al., 2021; Xing et al., 2020). Indeed, some cities in China had already benefited from such energy policies. For example, Shenzhen city in the PRD region has achieved the co-reductions of CO<sub>2</sub> and PM<sub>2.5</sub> by implementing strict

low-carbon policies in the power, industry, transportation, and building sectors (Development and Reform Commission of Shenzhen Municipality, 2012). The transition to clean energy and improved energy efficiency led to a 20% reduction in PM<sub>2.5</sub> from 2015 to 2019 and allowed Shenzhen to reach the period of decline of CO<sub>2</sub> emissions. In addition, different low-carbon strategies should be adopted rather than “one-size-fits-all” according to each city’s development level and economic structure. Developed cities are expected to focus on service-type activities and further improve energy efficiency and energy structure in building and transportation sectors. For cities with a higher-than-average development level, especially those manufacturing-oriented cities, they should adopt measures to improve energy efficiency in major industries (such as the iron and steel and the cement) and promote low-carbon technologies. For

those less developed or emerging cities, they could plan low-carbon strategies to potentially bypass the carbon-intensive growth. They could also utilize the advanced technology transferred from developed cities and construct their infrastructures in a sustainable way, which help reduce CO<sub>2</sub> emissions and minimize the “lock-in” effect in the long run (Wang et al., 2019).

Results from this study could potentially support achieving future air quality improvement and CO<sub>2</sub> emission reduction for all cities in China. Nonetheless, this study had several limitations. Our analysis was based on the CO<sub>2</sub> emissions and air pollutant concentration data in 2015 and 2019. The impacts of other influencing factors, such as the meteorology (L. Chen et al., 2020b) and population growth (Guo and Jiang, 2011), were not considered. Future research could be designed to examine their respective influence on CO<sub>2</sub> emission reduction and air quality improvement to complement current findings. In addition, CO<sub>2</sub> emissions were subject to uncertainties derived from the incompleteness of activity data and emission factors (Eggleston et al., 2016). A previous study suggested that the uncertainties of the Chinese city's GHG emissions, dominated by CO<sub>2</sub>, were in the range of 7.2% to 39.8% (Cai et al., 2019a). Thus, the data quality could be further improved by improving the CO<sub>2</sub> emission inventory in the future. Even with these limitations, our results are expected to have important policy implications on climate control and air quality improvement for cities in China and other countries facing similar dual challenges.

## 5. Conclusions

We used the city-level data to assess the changes of air quality and CO<sub>2</sub> emissions for 335 Chinese cities from 2015 to 2019. We found that city-level trends in PM<sub>2.5</sub>, O<sub>3</sub>, and CO<sub>2</sub> were not consistent. Mandatory city-level reduction targets were effective in reducing PM<sub>2.5</sub> concentrations, especially for cities in air pollution control regions such as the Beijing-Tianjin-Hebei region. However, O<sub>3</sub> increased in most cities likely due to the O<sub>3</sub>-NO<sub>x</sub>-VOC sensitivity regime, calling for implementing both NO<sub>x</sub> and VOC emission control measures. Developed cities showed CO<sub>2</sub> emission reductions mainly due to their energy intensity reduction and energy structure improvement. Less developed cities experienced rapid increases in CO<sub>2</sub> emissions due to economic development and less improvement in energy intensity. Our study found that current self-initiative low-carbon policies (“China's pilot low-carbon city” initiative) do not reduce CO<sub>2</sub> emissions effectively. To address both climate change and air pollution holistically, China should set mandatory city-level CO<sub>2</sub> emission reduction targets based on each city's development level and reinforce energy efficiency and clean energy measures.

## CRedit authorship contribution statement

**Li Zhang:** Conceptualization; Data curation; Methodology; Formal analysis; Visualization; Writing - original draft. **Pengcheng Wu:** Data curation; Software; Validation; Visualization. **Muchuan Niu:** Formal analysis; Writing - original draft. **Yixuan Zheng:** Methodology; Formal analysis. **Junxia Wang:** Data curation. **Guangxia Dong:** Data curation. **Zhe Zhang:** Data curation; Writing - original draft. **Zixuan Xie:** Data curation. **Mengbing Du:** Writing - original draft. **Hanying Jiang:** Writing - original draft. **Hui Liu:** Visualization. **Libin Cao:** Methodology. **Lingyun Pang:** Methodology. **Chen Lv:** Methodology. **Yu Lei:** Supervision; Writing - review & editing. **Bofeng Cai:** Conceptualization; Supervision; Visualization. **Yifang Zhu:** Conceptualization; Visualization; Supervision; Writing - review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2022.156274>.

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