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The Modeling Study about Impacts of Emission Control Policies for Chinese 14th Five-Year Plan on $PM_{2.5}$ and O_3 in Yangtze River Delta, China

Zhen Li [1], Shaocai Yu [1,2,*], Mengying Li [1], Xue Chen [1], Yibo Zhang [1], Zhe Song [1], Jiali Li [1], Yaping Jiang [1], Weiping Liu [1], Pengfei Li [3,*] and Xiaoye Zhang [1,4]

1 Research Center for Air Pollution and Health, Key Laboratory of Environmental Remediation and Ecological Health, Ministry of Education, College of Environment and Resource Sciences, Zhejiang University, Hangzhou 310058, China; liz@zju.edu.cn (Z.L.); 11814019@zju.edu.cn (M.L.); cxoldsnow@zju.edu.cn (X.C.); ybzhang903@zju.edu.cn (Y.Z.); song_zhe@zju.edu.cn (Z.S.); lijiali@zju.edu.cn (J.L.); jiangyaping@zju.edu.cn (Y.J.); wliu@zju.edu.cn (W.L.); xiaoye@cma.gov.cn (X.Z.)
2 Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, CA 91125, USA
3 College of Science and Technology, Hebei Agricultural University, Baoding 071001, China
4 State Key Laboratory of Severe Weather/Key Laboratory of Atmospheric Chemistry of China Meteorological Administration, Chinese Academy of Meteorological Sciences, Beijing 100081, China
* Correspondence: shaocaiyu@zju.edu.cn (S.Y.); lglpf@hebau.edu.cn (P.L.)

Abstract: The Chinese government has made great efforts to combat air pollution through the reductions in SO_2, NOx and VOCs emissions, as part of its socioeconomic Five-Year Plans (FYPs). China aims to further reduce the emissions of VOCs and NOx by 10% in its upcoming 14th FYP (2021–2025). Here, we used a regional chemical transport model (e.g., WRF/CMAQ) to examine the responses of $PM_{2.5}$ and O_3 to emission control policies of the 14th FYP in the Yangtze River Delta (YRD) region. The simulation results under the 4 emission control scenarios in the 2 winter months in 2025 indicate that the average concentrations of city mean $PM_{2.5}$ in 41 cities in the YRD were predicted to only decrease by 10% under both S1 and S1_E scenarios, whereas the enhanced emission control scenarios (i.e., S2_E and S3_E) could reduce $PM_{2.5}$ in each city by more than 20%. The model simulation results for O_3 in the 3 summer months in 2025 show that the O_3 responses to the emission controls under the S1 and S1_E scenarios show different control effects on O_3 concentrations in the YRD with the increase and decrease effects, respectively. The study found that both enhanced emission control scenarios (S2_E and S3_E) could decrease O_3 in each city by more than 20% with more reductions in O_3 under the S3_E emission control scenario because of its higher control strengths for both NOx and VOCs emissions. It was found that emission reduction policies for controlling high emission sectors of NO_x and VOCs such as S2_E and S3_E were more effective for decreasing both $PM_{2.5}$ and O_3 in the YRD. This study shows that O_3 controls will benefit from well-designed air pollution control strategies for reasonable control ratios of NOx and VOCs emissions.

Keywords: five-year-plan; emission control policy; Yangtze River Delta

Citation: Li, Z.; Yu, S.; Li, M.; Chen, X.; Zhang, Y.; Song, Z.; Li, J.; Jiang, Y.; Liu, W.; Li, P.; et al. The Modeling Study about Impacts of Emission Control Policies for Chinese 14th Five-Year Plan on $PM_{2.5}$ and O_3 in Yangtze River Delta, China. *Atmosphere* **2022**, *13*, 26. https://doi.org/10.3390/atmos13010026

Academic Editors: Zhe Wang, Zhenhao Ling, Jia Guo, Di Chang and Qinyi Li

Received: 30 November 2021
Accepted: 22 December 2021
Published: 25 December 2021

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1. Introduction

Ozone (O_3) and $PM_{2.5}$ (fine particles refer to particles with aerodynamic equivalent diameter less than or equal to 2.5 μm) are important pollutants of the troposphere due to their large impacts on air quality, human health and climate [1–4]. Both O_3 and $PM_{2.5}$ originate from complex sources and chemical reactions, and are very difficult to control [5,6]. The air pollution in China is the consequence of diverse and high primary emissions (e.g., NOx, NH_3, SO_2 and VOCs), and efficient secondary productions [7]. As a result of the rapid urbanization in the past decades, most regions in China have experienced heavy and even increasing O_3 and $PM_{2.5}$ pollutions [8–11]. Despite continued efforts, the Chinese government has yet to grapple with the issue of air pollution. The densely populated and developed regions experience frequent and severe winter haze and summer O_3 pollution episodes, such as the Beijing-Tianjin-Hebei (BTH), Pearl River Delta (PRD) and Yangtze River Delta (YRD) regions [12–15]. It has been shown that primary emissions accumulate in various types of meteorological conditions in each region, suggesting a strong tendency of complex air pollution in China [16,17]. Recent studies show that the changes in O_3 concentrations correlated with $PM_{2.5}$ reductions but that decreases in NOx led to unexpected rises in the surface O_3 level in China [18,19]. Studies have indicated that O_3 levels in eastern China show an obvious upward trend, with most of its urban agglomerations located in the YRD region [20,21]. The YRD region has 41 cities with the mega-city of Shanghai and the provinces of Jiangsu, Zhejiang and Anhui. The area accounts for only 2% of the national land area, but accounts for more than 20% of China's gross domestic product (GDP) [22]. It is one of the most densely populated and high-ground emission areas in China. Therefore, the region urgently needs control measures to curb the intensification of air pollution.

The Five-Year Plan, or FYP, is a comprehensive policy blueprint released by China every five years to guide its overall economic and social developments. During the 11th FYP (2004–2009), efforts were focused on reducing the emissions of SO_2 by setting an overarching goal to reduce national SO_2 emissions by 10% in the context of severe acid rain [23,24]. Since then, the overarching goal associated with air pollution control policies during each FYP period was repeatedly adjusted and set. For example, during the 12th FYP (2010–2015), the principal goal had been set to reduce 10% and 8% of the national NOx and SO_2 emissions, respectively. The main objectives of the 12th FYP were contextualized by the sharp increases in NOx emissions from motor vehicles in China which led to the intensification of air pollution [25,26]. After that, the overarching goal of the 13th FYP (2016–2020) was set to reduce 15%, 15%, and 10% of the national NOx, SO_2, and VOCs (volatile organic compounds) emissions, respectively. The 13th FYP marked the beginning of the overall emission reductions in VOCs. This is the first time that VOCs have been included in the overall emission reduction targets in the FYP. With the sharp rises in industrial products in China, there has been an increasing trend in domestic non-methane volatile organic compounds (NMVOCs) emissions [27]. VOCs are precursors to both surface-level ozone and secondary organic aerosols [28]. Meanwhile, due to the rise in industrial productions and the continuous promotion of urbanization, the continuous control of NOx and SO_2 emissions with the increased intensity of energy consumption are inevitable. The National People's Congress (NPC) of China formalized the "Outline for the 14th FYP and Long-Term Targets for 2035" in March, 2021. The outline of the 14th FYP sets the goal of reducing "energy intensity" by 13.5% between 2021 and 2025. This refers to China's long-term climate goal in the FYP and introduces the concept of "Capping Carbon Emissions" for the first time. The outline of the 14th FYP promulgates and implements the relevant emission reduction targets of comprehensively accelerating the controls of VOCs emissions and reducing the emissions of NOx and VOCs by more than 10%. With this background, this can represent possible emission reduction measures in China in the next five years. In general, the implementations of China's FYP ensures the stability of emission reductions at the national level.

In addition to the FYP, China has achieved remarkable results in air pollution controls with the implementation of the clean air policies. The detailed major clean air policies are summarized in Figure 1. For example, the "Air Pollution Prevention and Control Action Plan" (APPCAP, covering 2013–2017) was the most stringent air pollution prevention and control action plan promulgated in China. During this period, the $PM_{2.5}$ concentrations in the BTH, YRD, and PRD regions in 2018 relative to 2013 decreased by 25%, 20% and 15%, respectively [29]. In the five years, China had taken a series of strict air pollution control actions. However, there was a lack of control measures for the NMVOC emissions. Since then, China's State Council has promulgated the "Three-Year Action Plan for Winning the Blue Sky Defense Battle". By 2020, the total emissions of SO_2 and NOx would be reduced by more than 15% relative to those in 2015. It is expected that air quality can be significantly improved through the implementation of air quality policies. Despite China's efforts to reduce emissions, China's air quality was still far below the requirements of residents and the targets promised by the government. Therefore, flexible and scientific emission reduction policies are needed to prevent the deterioration of air pollution in China.

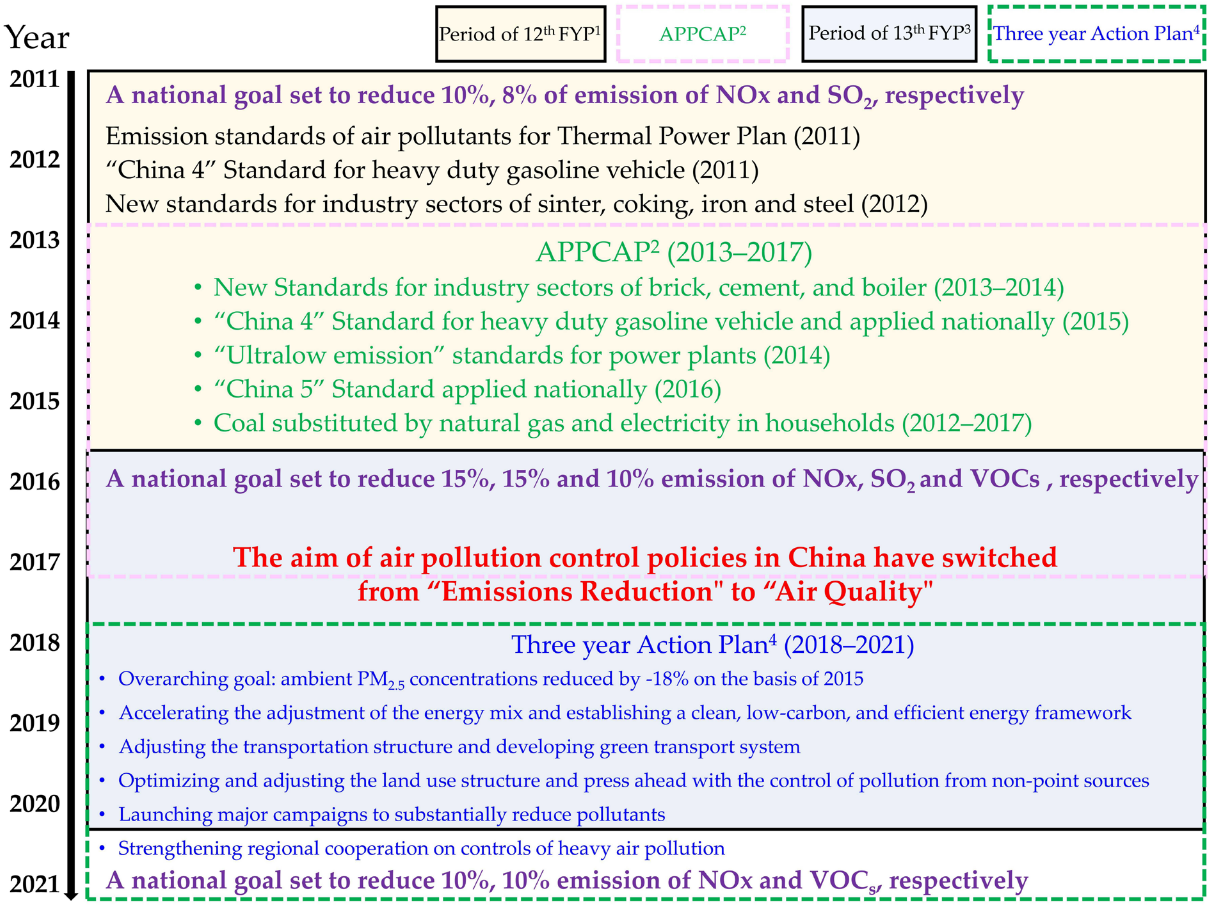

Figure 1. Timeline summarizing major air pollution control strategies in China. 1 The 12th Five Year Plan (2010–2015), the overarching goal was set to reduce 10% and 8% national NOx and SO_2 emission with a result of 18.6% and 18% reductions in national NOx and SO_2 emissions, respectively. 2 Air Pollution Prevention and Control Action Plan (2013–2017) aimed to reduce 25%, 20% and 15% $PM_{2.5}$ in Beijing-Tianjin-Hebei region (BTH), YRD (YRD) and Pearl River Delta (PRD), respectively. 3 The 13th Five Year Plan (2016–2020), the overarching goal was set to reduce 15%, 15% and 10% national NOx, SO_2, and VOCs emission, respectively. 4 Three-Year Action Plan for Winning the Blue Sky Defense Battle (2018–2021). The Action Plan puts forward six measures with quantifiable indicators and timelines. After that, the overarching goal was set to reduce 10% and 10% national NOx and VOCs emission in the 14th Five Year Plan (2021–2025), respectively.

The advanced chemical transport model can be used to estimate the level of air pollutants and provide strong support for the simulation of air pollution control policies. However, there is still a lack of relevant studies reflecting on the actual ground emission status and the effective emission reduction strategies in the FYP. This study systematically evaluated the impacts of the implementation of the air quality policies in the 14th FYP in the YRD by 2025. The simulation periods mainly focused on the summer season (June-July-August) with the ozone pollution and the winter season (January and December) with the haze pollution in the YRD. The significance of this study is to provide the reference and basis for the future air pollution policy-making. We comprehensively analyzed the formation of O_3 and $PM_{2.5}$ during the "14th FYP" period and under the background of

"Capping Carbon Emissions" for the first time. The results reveal the specific targets of emission reductions in the YRD in the future, and will also provide enlightenments for the formulation of China's future emission reduction policies

2. Methods

2.1. Model Configurations and Emission Inventory

The offline Weather Research and Forecasting (WRFv3.9.1) and Community Multi-scale Air Quality Modeling (CMAQv5.3.2) model was applied to simulate spatiotemporal variations in meteorological and chemical fields. The CMAQv5.3.2 (released in 2020) is the latest version and its major science advances in detail can be found in Murphy et al. [30], and Appel et al. [31]. In this study, the Carbon Bond 6 (CB6) schemes and AERO7 module were responsible for gas and aerosol chemistry simulations, respectively. More advanced scientific calculation functions were embedded into CB6 and AERO7 for improving organic aerosol simulation performance of CMAQv5.3.2. Compared to CB5 with 74 species and 182 reactions, CB6 contains 90 species and 227 reactions for the gas-phase precursors [32,33]. Fewer species are required for AERO7 with more robust predictions which require less computation time than AERO6. Scientific improvements in AERO7 include [34]: (1) improvements in consistency in terms of secondary organic aerosol (SOA) between carbon bond and SAPRC-based mechanisms; (2) updates of monoterpene SOA from photooxidation (OH and ozone); (3) uptakes of water onto hydrophilic organics; (4) reorganization of anthropogenic SOA species and (5) formations of inorganic sulfate when IEPOX organosulfates are formed.

A 1-way domain covering mainland China with a horizontal resolution of 12 km $\times$ 12 km was built, which had 345 rows and 395 columns of grid cells (Figure S1). The projection mode was Lambert for the domain. The inorganic components were computed by the ISORROPIA II module [35]. The WRFv3.9.1 model was used to provide meteorological fields for chemical simulations [36]. The model configurations and components for the WRF model used in this study were the same as those in Yu et al. [37], Zhang et al. [38] and Wang et al. [39].

To study the impacts of emission control policies of the 14th FYP on the air quality in the YRD in 2025, the meteorological initial conditions (IC) and boundary conditions (BC) for the WRF model were derived from the model results on the basis of the "Representative Concentration Pathways" (RCP) Database (version 2.0) for the RCP 8.5 in 2025 simulated by the MESSAGE modeling team [40]. The underlying scenario drivers and resulting development paths for the RCP 8.5 were based on the A2r scenario detailed in Riahi et al. (2007) which characterized increasing greenhouse gas emissions over time representative of scenarios in the literature, leading to high greenhouse gas concentration levels [41]. RCP8.5 is consistent with the policy background under the Paris Agreement and the timeline of large-scale economic change and focuses on the total cumulative CO_2 emissions between 2005 and 2030 [41,42]. China is expected to achieve its commitment of "Capping Carbon Emissions" before 2030. In the context of "Capping Carbon Emissions" background, RCP8.5 was chosen in the study. The RCP database is available from the open-source website [43].

The gridded anthropogenic emissions for China from the Emission Inventory of Air Benefit and Cost and Attainment Assessment System (EI-ABaCAS) in 2018, developed by Tsinghua University [44], were used. The EI-ABaCAS includes 16 emission sectors listed in Table S1 The EI-ABaCAS dataset includes the annual gridded emissions on a Lambert projection grid with 12 km resolution, which is consistent with the resolution of the model domain. The emissions for CO, NH_3, NOx, PM_{10}, $PM_{2.5}$, SO_2, and VOCs with speciation were contained in the dataset. The total annual emissions for various industry sectors for each province in the YRD were summarized in Figure 2 and Table S2. The natural sources for biogenic emissions were calculated inline using the Biogenic Emission Inventory System version 3.14 (BEISv3.14) [45].

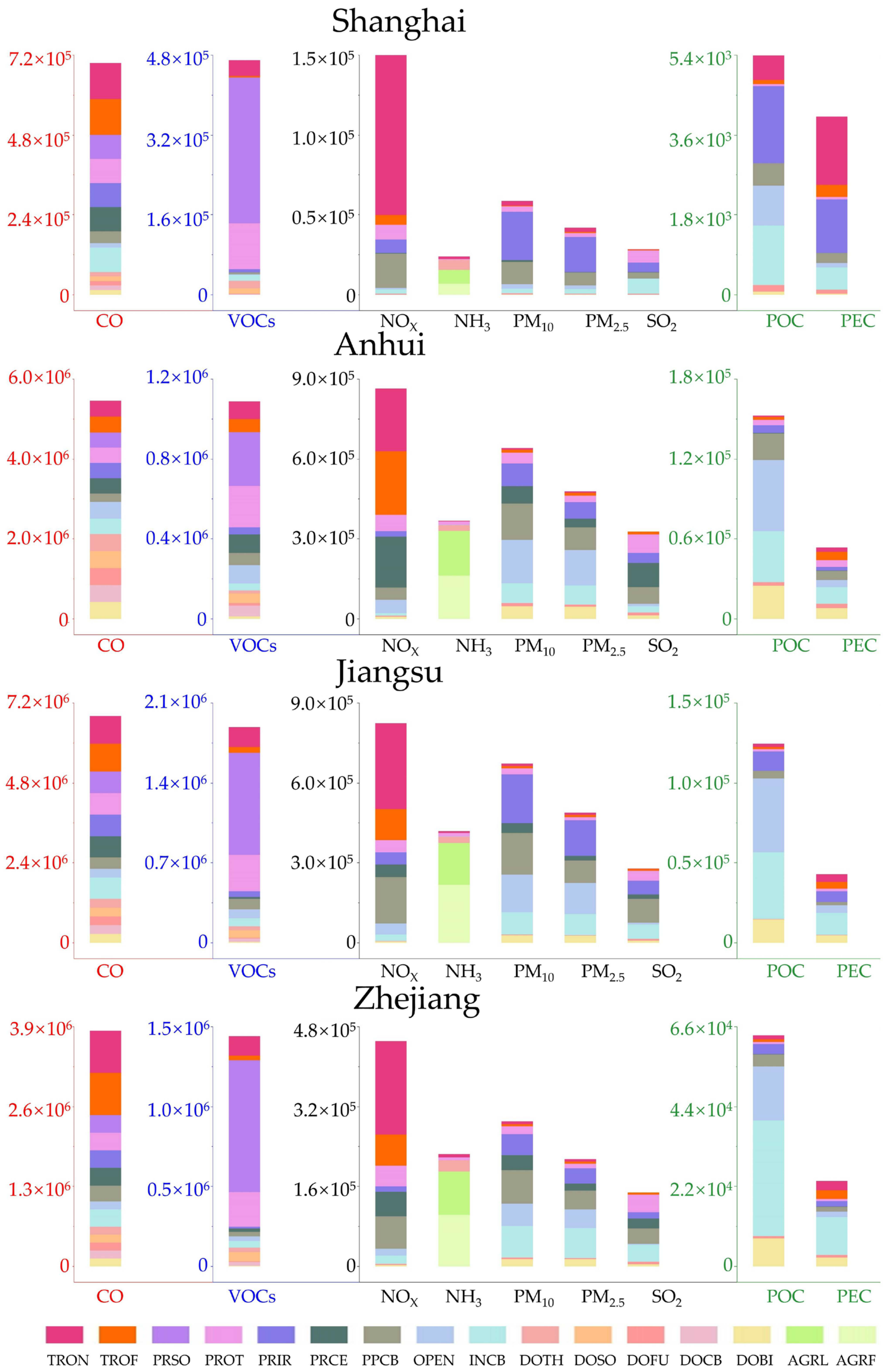

Figure 2. The histogram of 16 sectors of annual emissions in 2018 for each species (CO, VOCs, NOx, NH_3, PM_{10}, $PM_{2.5}$, SO_2, POC and EC) in Shanghai, Anhui, Jiangsu, and Zhejiang in the YRD. The unit of emission is tons/year (t/a). The descriptions of 16 emission sectors were listed in Table S1.

The YRD urban agglomerations includes 26 cities, as shown in Figure S1, with city names listed in Table S3. Hourly observed $PM_{2.5}$ and O_3 concentrations in 26 cities between 2016 and 2021 were obtained from China National Environmental Monitoring Center [46]. The monthly average and maximum concentrations of $PM_{2.5}$ and O_3 for each city in the YRD in the past 6 years (2016–2021) were shown in Figures S2 and S3, which provided insight into the historical air pollutions in YRD. Based on the results of the pollution situation in the past 6 years (Figures S2 and S3), the high concentrations of $PM_{2.5}$ and O_3 in the YRD occurred in the 2 winter months (i.e., January and December) and the 3 summer months (i.e., June, July, and August), respectively. Hence, we chose two winter months (January and December) to represent the haze formation period and three summer months (June, July and August) to represent the O_3 pollution period in the YRD in this study.

2.2. Descriptions of Emission Control Scenarios

Our study designed two types of experiments, namely baseline and sensitivity scenario simulations. In the baseline scenario simulations (case: Base), the original emission inventory without any emission controls were used. We designed 4 sets of sensitivity scenario simulations (S1, S1_E, S2_E and S3_E) to quantify the potential impacts of emission control policies in the 14th FYP on both $PM_{2.5}$ and O_3 in the YRD as listed in Tables 1 and 2. These four emission control scenarios are described in detail below.

The Chinese government sets targets for the performance of its economy in every Five-Year Plan (FYP), which include energy- and pollution-related targets from the National Total Emissions Control (NTEC) Program. In the 13th FYP, the national SO_2, NOx and VOCs targets were set to achieve 15%, 15%, and 10% emission reductions, respectively. Nevertheless, the actual reduction varied across the country. Local governments all over the country had reported their emission reduction results of NTEC to Ministry of Ecology and Environment of China by 2020 since this was the last year of the 13th FYP. The emission control scenario 1 (S1) was designed on the basis of the reported emission reduction results in 41 cities in the YRD listed in Table 1. Under the guidance of ecosystem and environmental protections in the 14th FYP [47], the governments of Shanghai, Anhui, Jiangsu and Zhejiang have formulated emission control policies to prevent and control air pollution for protecting the air environment and public health with quantifiable indexes and time nodes [48–51]. The 5 main policies are briefly summarized below [48–51]: (1) Adjustments and optimizations of the energy structures. By 2025, the proportion of non-fossil and clean energies in primary energy production and consumption will reach more than 20%. (2) Implementation of comprehensive managements of industrial boilers and other industries. This policy is the continuation of the "ultra-low emission" work, including the phasing out and renovation of old boilers in the YRD. (3) Integrated management of industrial parks. The policy will gradually promote emission reductions for industries with the high VOCs emissions. (4) Developments of green transportation systems in the YRD. By 2023, the "China 6" standard for motor vehicles will be fully implemented. The share of railway freight transportation will increase to 35%, and the market share of "new energy vehicles" will reach 20% by 2025. (5) Strengths of the comprehensive management of VOCs emissions in the YRD. This includes the substitution of raw materials and the upgrading projects of inefficient treatment facilities with high VOCs emissions. The enhanced emission control scenario (S1_E) was designed by assuming that the above 5 measures would be fully implemented in all cities in the YRD by 2025. To summarize briefly, the total emission reductions are assumed to increase by 1.5, 1.5 and 3 times for NOx, SO_2, and VOCs in S1_E relative to those in S1, respectively.

Table 1. The emission control schemes on the basis of National Total Emission Controls.

Province	City	Control Scenario 1 (S1)			Enhanced Control Scenario 1 (S1_E)		
		SO_2	NO_X	VOCs	SO_2	NO_X	VOCs
municipal	Shanghai	20.0%	20.0%	20.0%	30.0%	30.0%	60.0%
Anhui	Anqing	16.0%	14.4%	11.4%	24.0%	21.6%	34.2%
	Bengbu	15.4%	13.2%	10.4%	23.1%	19.8%	31.2%
	Bozhou	11.0%	8.8%	6.6%	16.5%	13.2%	30.0%
	Chizhou	5.0%	6.0%	8.8%	7.5%	9.0%	30.0%
	Chuzhou	13.2%	15.4%	9.1%	19.8%	23.1%	30.0%
	Fuyang	11.2%	14.4%	7.9%	16.8%	21.6%	30.0%
	Hefei	23.1%	24.2%	12.2%	34.7%	36.3%	36.6%
	Huaibei	17.6%	16.0%	9.9%	26.4%	24.0%	30.0%
	Huainan	17.9%	17.6%	6.8%	26.9%	26.4%	30.0%
	Huangshan	2.0%	2.0%	10.3%	3.0%	3.0%	30.9%
	Luan	8.8%	8.0%	8.6%	13.2%	12.0%	30.0%
	Mananshan	23.1%	24.2%	12.4%	34.7%	36.3%	37.2%
	Suzhou	22.0%	22.0%	22.0%	33.0%	33.0%	66.0%
	Tongling	17.6%	17.6%	9.8%	26.4%	26.4%	30.0%
	Wuhu	17.9%	17.6%	11.6%	26.9%	26.4%	34.8%
	Xuancheng	8.5%	10.0%	9.9%	12.8%	15.0%	30.0%
Jiangsu	Changzhou	20.0%	20.0%	20.0%	30.0%	30.0%	60.0%
	Huaian	20.0%	20.0%	20.0%	30.0%	30.0%	60.0%
	Lianyungang	20.0%	20.0%	20.0%	30.0%	30.0%	60.0%
	Nanjing	20.0%	20.0%	20.0%	30.0%	30.0%	60.0%
	Nantong	20.0%	20.0%	20.0%	30.0%	30.0%	60.0%
	Suqian	20.0%	20.0%	20.0%	30.0%	30.0%	60.0%
	Suzhou	12.1%	11.0%	8.4%	18.2%	16.5%	30.0%
	Taizhou	22.0%	22.0%	22.0%	33.0%	33.0%	66.0%
	Wuxi	22.0%	22.0%	22.0%	33.0%	33.0%	66.0%
	Xuzhou	22.0%	22.0%	22.0%	33.0%	33.0%	66.0%
	Yancheng	18.0%	18.0%	18.0%	27.0%	27.0%	54.0%
	Yangzhou	20.0%	20.0%	20.0%	30.0%	30.0%	60.0%
	Zhenjiang	20.0%	20.0%	20.0%	30.0%	30.0%	60.0%
Zhejiang	Hangzhou	23.0%	23.0%	26.0%	34.5%	34.5%	78.0%
	Huzhou	23.0%	23.0%	20.0%	34.5%	34.5%	60.0%
	Jiaixng	21.0%	21.0%	18.0%	31.5%	31.5%	54.0%
	Jinhua	21.0%	21.0%	26.0%	31.5%	31.5%	78.0%
	Lishui	8.0%	8.0%	24.0%	12.0%	12.0%	72.0%
	Ningbo	17.0%	17.0%	25.0%	25.5%	25.5%	75.0%
	Quzhou	15.0%	15.0%	24.0%	22.5%	22.5%	72.0%
	Shaoxing	22.0%	22.0%	18.0%	33.0%	33.0%	54.0%
	Taizhou	13.0%	13.0%	3.0%	19.5%	19.5%	30.0%
	Wenzhou	15.0%	15.0%	15.0%	22.5%	22.5%	45.0%
	Zhoushan	3.0%	3.0%	10.0%	4.5%	4.5%	30.0%

Table 2. The emission control scheme on the basis of controls of emission sectors.

Control Scenario	Description	Sectors *	Control Percentage (%)								
			CO	NH_3	NOx	PEC	PM_{10}	$PM_{2.5}$	POC	SO_2	VOCs
S2_E	Enhanced control	AGRF		10.0%							
		AGRL		10.0%							
		INCB	20.0%		20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	
		PPCB	30.0%		30.0%	20.0%	20.0%	20.0%	20.0%	20.0%	
		PRCE	30.0%		30.0%	30.0%	30.0%	30.0%	30.0%	30.0%	
		PRIR	20.0%		20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	
		PROT	20.0%		20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	50.0%
		PRSO									50.0%
		TROF	30.0%		30.0%	30.0%	30.0%	30.0%	30.0%	30.0%	30.0%
		TRON	30.0%		30.0%	30.0%	30.0%	30.0%	30.0%	30.0%	30.0%
S3_E	Enhanced control	AGRF		20.0%							
		AGRL		20.0%							
		INCB	35.0%		35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	
		PPCB	35.0%		35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	
		PRCE	50.0%		50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	
		PRIR	35.0%		35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	
		PROT									65.0%
		PRSO									65.0%
		TROF	50.0%		50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%
		TRON	50.0%		50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%
S2_E_NT	Enhanced control No transport control	AGRF		10.0%							
		AGRL		10.0%							
		INCB	20.0%		20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	
		PPCB	30.0%		30.0%	20.0%	20.0%	20.0%	20.0%	20.0%	
		PRCE	30.0%		30.0%	30.0%	30.0%	30.0%	30.0%	30.0%	
		PRIR	20.0%		20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	
		PROT	20.0%		20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	50.0%
		PRSO									50.0%
		TROF	\	\	\	\	\	\	\	\	\
		TRON	\	\	\	\	\	\	\	\	\
S3_E_NT	Enhanced control No transport control	AGRF		20.0%							
		AGRL		20.0%							
		INCB	35.0%		35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	
		PPCB	35.0%		35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	
		PRCE	50.0%		50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	
		PRIR	35.0%		35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	
		PROT									65.0%
		PRSO									65.0%
		TROF	\	\	\	\	\	\	\	\	\
		TRON	\	\	\	\	\	\	\	\	\

* Emission sectors include Agriculture: AGRF (fertilizer application), AGRL (livestock); Industry: INCB (industry combustion), PRCE (cement), PRIR (steel), PRSO (industry solvent use), PROT (other industry process); Energy: PPCB (power plant); Transport: TROF (off-road transport), TRON (on-road transport).

To explore the impact on pollutant generations under the premise that all the induced policies and relevant advanced emission source control technologies will be fully implemented in the high-emission sectors of the YRD by 2025, 2 emission control scenarios (S2_E and S3_E) were designed on the basis of controls schemes for emission sectors as listed in Table 2. These include emission sectors for Agriculture (AGRF (fertilizer application), AGRL (livestock)), Industry (INCB (industry combustion), PRCE (cement), PRIR (steel), PRSO (industry solvent use), PROT (other industry process)), Energy PPCB (power plant)) and Transport (TROF (off-road transport), TRON (on-road transport)) (see Table 2). Relative to S1_E, S2_E had more types of pollutants regulated and the control rates of pollutants adjusted within the scope of policy implementation. Relative to S2_E, S3_E maintained the same control set for the emission sectors but with higher control rates as shown in Table 2. The corresponding reduction rates for each species of each emission sector in Table 2 were derived on the basis of targets for air quality improvement, key air pollutant emission reductions and the optimization of energy and industrial structures for 2025 in the 14th Five-Year Plan. The high emissions of NH_3 come from livestock farming and the heavy use of fertilizers. A combination of the aforementioned measures was estimated to reduce China's NH_3 emissions by 30–50%, based on the existing literature and local agricultural practice [52]. In this work, we choose 10% and 20% NH_3 emission abatement strategy to examine its atmospheric environmental impacts for S2_E and S3_E, respectively.

The controls of O_3 precursors were mainly focused on NOx emissions, whereas less emission control strategies have been implemented on VOCs in the past few decades in China. However, along with the vigorous promotion of a green public transportation system, and new energy automobile in YRD, the NOx emissions from transportation will fall further in the future. In addition, NOx emissions in China have decreased by 23% since 2016, in which emission reductions from power plants were the predominant contributor [19]. Hence, China will continue to implement NOx emission abatement policies. In this study, 30–50% NOx emission reductions for industry and transportation sectors were chosen in S2_E and S3_E. A percentage of 50% can be taken as of upper bound of NOx emission reductions via feasible control policies in the 14th FYP in Table 2. The large-scale regulations in VOCs emissions in China started in 2018. These regulations had been included in the Three-Year Action Plan for Winning the Blue Sky Defense Battle (covering 2018–2021). The regulations include: (1) Remediation plans for key VOC-emitting industries; (2) Banning the production and use of high-VOC solvent-based inks, adhesives, etc.; (3) Enforcement actions to reduce the total environmental emissions of certain VOCs by more than 10 percent between 2015–2020. In March 2020, China released 4 mandatory national standards on VOCs in coatings, adhesives, inks, and cleaning agents [53]. These standards, which come into effect on 1 December 2020, include: (1) GB 30981-2020, "Limit of harmful substances of industrial protective coatings"; (2) GB 33372-2020, "Limit of volatile organic compounds content in adhesives"; (3) GB 38507-2020, "Limits of volatile organic compounds (VOCs) in printing inks", and (4) GB 38508-2020, "Limits for volatile organic compounds content in cleaning agents". On the basis of this information, high VOCs control rates with 30–65% in industry and transportation sectors were used under the S2_E and S3_E control scenarios in this study (see Table 2). From 2013 to 2017, significant declines in $PM_{2.5}$ concentrations occurred nationwide [29]. Therefore, we chose comparatively low control rates (20–35%) of primary particulate pollutants (PEC, PM_{10}, $PM_{2.5}$ and SO_2) from industry sectors under the S2_E and S3_E control scenarios in this study (see Table 2). In the context of "Carbon Peaking and Neutrality", the comprehensive carbon emission control should be promoted in China. The CO control rates were kept the same as primary particulate pollutants with 20–50% (see Table 2). As shown in Table 2, the S3_E case can be considered as the enhanced emission control scenario of S2_E.

On the other hand, the S2_E_NT and S3_E_NT scenarios were created to test the sensitivities of O_3 to VOCs and NOx emissions from the transportation sector by completely removing the transportation emission sources (TROF and TRON) in the corresponding emission control scenarios of S2_E and S3_E (see Table 2).

3. Results and Discussions

3.1. Impacts of the Emissions Control Scenarios on $PM_{2.5}$ in the YRD

The potentials of emission control scenarios for air quality improvement in the YRD region were evaluated by comparing the simulations of surface concentrations of city mean $PM_{2.5}$ in 41 cities under the 4 control and 1 baseline scenarios in the 2 winter months (January and December) in 2025. Table 3 summarizes the predicted average decreases in city mean $PM_{2.5}$ concentrations in 41 cities under the 4 different emission control scenarios relative to the base case in the 2 winter months, while Tables S4 and S5 listed the monthly mean results for each month. The spatial distributions of the predicted average changes in concentrations and percentages of mean $PM_{2.5}$ in the 2 winter months were shown in Figure 3 and Figure S4, respectively. Figure 3 indicates that although the scenarios of enhanced emission controls (S1_E and S3_E) show further decreases in mean $PM_{2.5}$ concentrations in line with expectations, the decrease values were different in the different regions.

Table 3. Predicted average decrease values of winter $PM_{2.5}$ concentrations under the 4 control scenarios relative to the baseline in 41 main cities of YRD in 2025.

		Base	**S1-Base**	**S1_E-Base**	**S2_E-Base**	**S3_E-Base**
Province	**City**	**Concentrations * (μg/m³)**	**Decrease Values * (μg/m³)**			
municipal	Shanghai	30.0 ± 27.7	−0.3 ± 1.7	−1.1 ± 2.5	−4.8 ± 4.7	−9.1 ± 8.7
Anhui	Anqing	63.7 ± 59.7	−0.2 ± 1.6	−4.0 ± 12.0	−8.7 ± 10.2	−8.0 ± 13.6
	BengBu	38.1 ± 38.8	−0.6 ± 2.7	−0.5 ± 2.0	−9.0 ± 10.0	−11.5 ± 12.4
	Bozhou	42.4 ± 41.8	−0.2 ± 1.8	−3.0 ± 9.7	−10.0 ± 10.4	−13.1 ± 14.7
	Chizhou	23.8 ± 25.1	−0.3 ± 1.2	−1.7 ± 5.1	−12.3 ± 13.8	−9.6 ± 12.1
	Chuzhou	53.6 ± 53.0	−0.1 ± 1.0	−2.1 ± 5.7	−8.2 ± 7.3	−9.9 ± 12.6
	Fuyang	34.9 ± 34.2	−0.2 ± 0.8	−1.3 ± 3.2	−10.5 ± 10.8	−10.6 ± 14.1
	Hefei	32.9 ± 28.9	−0.8 ± 2.8	−0.7 ± 2.6	−10.2 ± 10.7	−12.9 ± 17.5
	Huaibei	35.0 ± 39.4	−0.2 ± 1.2	−1.5 ± 4.8	−9.1 ± 9.6	−9.2 ± 11.5
	Huainan	29.8 ± 34.6	−0.2 ± 0.9	−0.7 ± 2.3	−9.6 ± 10.8	−6.3 ± 9.2
	Huangshan	38.3 ± 37.4	0.0 ± 1.0	−1.7 ± 6.4	−11.2 ± 13.2	−7.0 ± 6.4
	Luan	46.0 ± 46.3	−0.1 ± 0.4	−0.8 ± 1.6	−9.0 ± 9.5	−8.4 ± 7.1
	Maanshan	48.9 ± 50.4	0.1 ± 1.0	−3.9 ± 9.1	−6.8 ± 6.8	−10.8 ± 15.4
	Suzhou	33.0 ± 30.3	−0.1 ± 0.9	−2.1 ± 9.3	−9.2 ± 9.1	−10.2 ± 11.5
	Tongling	51.3 ± 46.9	−0.1 ± 0.9	−2.6 ± 8.1	−7.1 ± 7.2	−8.4 ± 10.5
	Wuhu	53.7 ± 50.0	−0.5 ± 1.5	−2.2 ± 7.1	−5.9 ± 5.5	−6.4 ± 6.2
	Xuancheng	49.9 ± 47.0	−0.2 ± 1.7	−2.0 ± 6.4	−11.1 ± 12.7	−7.6 ± 9.2
Jiangsu	Changzhou	57.2 ± 54.9	−0.3 ± 1.9	−2.6 ± 7.3	−10.8 ± 11.6	−6.5 ± 9.2
	Huaian	48.6 ± 44.7	−0.2 ± 1.0	−2.1 ± 7.9	−11.6 ± 12.5	−11 ± 12.9
	Lianyungang	41.2 ± 41.4	−0.2 ± 0.9	−1.5 ± 5.7	−7.1 ± 6.5	−7.3 ± 8.6
	Nanjing	39.3 ± 38.8	−0.4 ± 1.9	−2.4 ± 9.8	−11.4 ± 10.8	−10.1 ± 11.2
	Nantong	35.1 ± 33.8	−0.2 ± 0.3	−1.6 ± 5.4	−10.6 ± 10.6	−9.2 ± 9.8
	Suqian	38.6 ± 37.2	0.1 ± 1.1	−2.2 ± 6.1	−11.9 ± 12.1	−9.9 ± 12.3
	Suzhou	59.1 ± 55.9	−0.2 ± 0.3	−1.7 ± 5.1	−13.1 ± 13.9	−10.7 ± 12.9
	Taizhou	51.4 ± 47.0	−0.1 ± 0.9	−1.8 ± 5.6	−6.8 ± 7.7	−11.0 ± 11.8
	Wuxi	43.3 ± 41.7	−0.5 ± 1.7	−1.2 ± 4.9	−4.6 ± 4.9	−9.7 ± 10.7
	Xuzhou	54.4 ± 55.4	−0.3 ± 1.8	−0.3 ± 0.9	−8.7 ± 8.5	−11.0 ± 12.0
	Yangzhou	47.0 ± 44.2	−0.1 ± 0.3	−3.3 ± 9.3	−5.9 ± 5.9	−10.5 ± 12.3
	Yancheng	31.0 ± 28.1	−0.1 ± 1.2	−1.7 ± 5.5	−9.8 ± 10.2	−7.8 ± 14.5
	Zhenjiang	49.2 ± 44.6	−0.4 ± 1.8	−3.0 ± 8.2	−10.1 ± 10.6	−4.9 ± 5.0
Zhejiang	Hangzhou	56.8 ± 52.9	−0.2 ± 1.1	−1.6 ± 5.9	−9.2 ± 8.2	−13.5 ± 15.3
	Huzhou	55.3 ± 51.6	0.0 ± 0.6	−1.5 ± 5.2	−9.9 ± 10.2	−8.5 ± 8.3
	Jiaxing	43.5 ± 39.5	−0.3 ± 1.3	−2.3 ± 8.8	−10.8 ± 11.5	−3.9 ± 3.8
	Jinhua	61.4 ± 55.6	0.1 ± 1.2	−1.3 ± 4.4	−9.2 ± 8.1	−12.4 ± 13.2
	Lishui	19.7 ± 16.9	−0.1 ± 1.0	−1.3 ± 3.1	−8.3 ± 10.0	−10.4 ± 12.2
	Ningbo	46.9 ± 44.9	0.1 ± 1.0	−2.9 ± 9.0	−12.0 ± 12.2	−11.4 ± 13.2
	Quzhou	44.7 ± 40.8	−0.2 ± 1.0	−1.3 ± 4.8	−5.7 ± 5.5	−10.5 ± 13.6
	Shaoxing	44.4 ± 48.6	−0.1 ± 1.1	−0.4 ± 0.8	−10.6 ± 10.9	−11.7 ± 13.9
	Taizhou	41.9 ± 41.0	0.0 ± 1.1	−2.4 ± 10.1	−5.3 ± 5.1	−10.7 ± 12.7
	Wenzhou	53.6 ± 50.6	−0.1 ± 0.3	−1.3 ± 2.8	−8.6 ± 9.1	−9.3 ± 9.2
	Zhoushan	47.9 ± 42.0	0.0 ± 1.2	−1.3 ± 4.1	−8.8 ± 10.7	−10.7 ± 12.5

Concentrations *: monthly mean concentrations ± standard deviation. Decrease values *: monthly mean decrease values ± standard deviation.

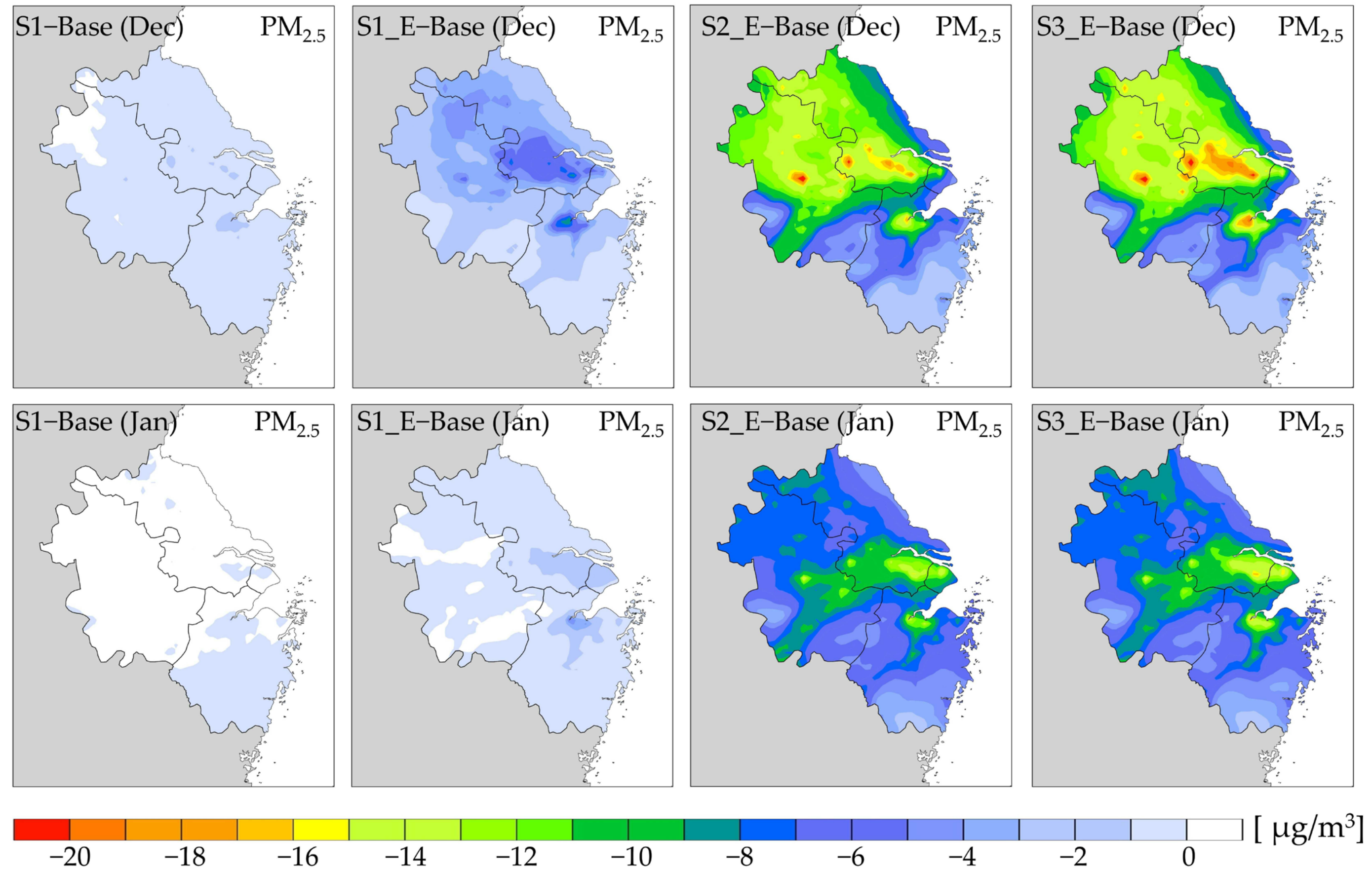

Figure 3. Spatial distributions of $PM_{2.5}$ concentration decrease values under the 4 control scenarios relative to the base case over the YRD region in January (Jan) and December (Dec), 2025.

Overall, the $PM_{2.5}$ decreases in these 41 cities in December were larger than those in January for the same control scenarios. Compared to the S1 scenario, the S1_E scenario had wider decrease areas and higher decrease values of $PM_{2.5}$ concentrations (Figure 3), consistent with the intensities of emission controls (Tables 1 and 2). In January, under the scenarios of S2_E and S3_E, the $PM_{2.5}$ decreases in the central Anhui, southern Jiangsu, northern Zhejiang and Shanghai were relatively large. Under the S1 scenario designed on the basis of the emission reduction scheme reported in the 13th FYP, the average $PM_{2.5}$ decreases in these 41 cities in the YRD in winter were less than 2 $\mu g/m^3$. Under the S1_E scenario, the monthly average concentrations of city mean $PM_{2.5}$ were predicted to decrease by -7.6 $\mu g/m^3$ in Anqing city of Anhui province, followed by -5.8 $\mu g/m^3$ in Ningbo city of Zhejiang province, -5.4 $\mu g/m^3$ in Zhenjiang city of Jiangsu province, and -1.4 $\mu g/m^3$ in Shanghai in December (see Table S4). Compared with those in December, the decrease values in January were expected to be less due to its lower baseline concentrations. For example, it was predicted that by January 2025, under the S1_E scenario, the maximum values of average decreases in city mean $PM_{2.5}$ in each province in both Suzhou city (in Anhui province) and Yangzhou city (in Jiangsu province) would reach -3.5 $\mu g/m^3$, followed by -1.1 $\mu g/m^3$ in Jiaxing city of Zhejiang province and -0.7 $\mu g/m^3$ in Shanghai. As shown in Figure S4, under the S1 and S1_E scenarios, the decrease percentages of $PM_{2.5}$ in the YRD were predicted to be less than 10%. Although the overall emission reductions in SO_2, NOx and VOCs in the YRD were strengthened under the S1_E scenario, the average concentrations of city mean $PM_{2.5}$ were predicted to decrease only by 10% by 2025, indicating that the emission reduction intensities under the S1_E scenario were not enough to meet the requirements of the 14th FYP.

Compared to the control scenarios of S1 and S1_E, the enhanced emission control scenarios (i.e., S2_E and S3_E) are expected to further reduce $PM_{2.5}$ in each city by more than 20%, depending on the regions and months (see Figure S4). For example, the S3_E control scenario led to a further decrease in monthly average $PM_{2.5}$ concentrations in Shanghai, Anhui, Jiangsu, and Zhejiang in December of 2025 by −3.1, −14.9 to −3.6, −17.3 to −2.6, and −12.6 to −3.4 μg/m^3 in December of 2025, respectively (Table S4). The predicted decreases in $PM_{2.5}$ in January were different from those in December, with smaller decreases expected in the most areas of the YRD due to their lower $PM_{2.5}$ concentrations (Figure 3 and Table S5). It was clear that when the precursor reductions were high, it would lead to a concentration decrease in more areas with higher reductions (Figure 3). Compared with the S2_E scenario, the monthly average decreases in $PM_{2.5}$ in the YRD region for 2 months under the S3_E scenario were larger. For example, reductions were expected to decrease further by 8.3 μg/m^3 in Hangzhou and Anqing under the S3_E scenario, with more decreases in most other cities (Tables S4 and S5). In summary, the decrease values of the emission control policies predicted by the S1 and S1_E scenarios were not enough, and the decreases in city mean $PM_{2.5}$ concentrations in the most regions of YRD in the winter of the 14th FYP were less than 20%, based on the monthly simulation results (Figure S4). As shown above, the enhanced emission control scenarios (i.e., S2_E and S3_E) will be an effective way for decreasing $PM_{2.5}$ in the YRD region.

3.2. Impacts of the Emissions Control Scenarios on O_3 in the YRD

Figures 4 and 5 depict the monthly mean changes in hourly and MDA8 (the maximum daily 8-hour moving average) O_3 concentrations under the S1 and S1_E scenarios relative to the base case in June, July and August of 2025. Tables 4 and 5 summarize the mean results in all 3 months for each city of the 41 cities in the YRD and the results for each month are listed in Tables S6–S11. The S1 and S1_E control emission reduction policies have completely different emission reduction effects for O_3 relative to those of $PM_{2.5}$ in the YRD. Under the S1 scenario, O_3 mean concentrations in the most areas of the YRD showed increasing trends with decreases in precursor emissions. It was found that the maximum monthly mean increases in city mean O_3 concentrations in Shanghai, Anhui, Jiangsu and Zhejiang in the 3 summer months under the S1 scenario were 7.8 μg/m^3 (in July in Shanghai), 15.0 μg/m^3 (in August in Bengbu city), 12.9 μg/m^3 (in August in Zhenjiang city), and 13.8 μg/m^3 (in July in Lishui city), respectively (see Tables S6–S8). The increasing trends were more obvious for the MDA8 O_3 concentrations (Figure 5). The maximum monthly increases in city MDA8 O_3 concentrations in Shanghai, Anhui, Jiangsu, and Zhejiang in 3 summer months under the S1 scenario were 29.5 μg/m^3 (in July in Shanghai city), 39.7 μg/m^3 (in August in Fuyang city), 29.5 μg/m^3 (in June in Nantong city) and 28.7 μg/m^3 (in August in Shaoxing city), respectively (Tables S9–S11).

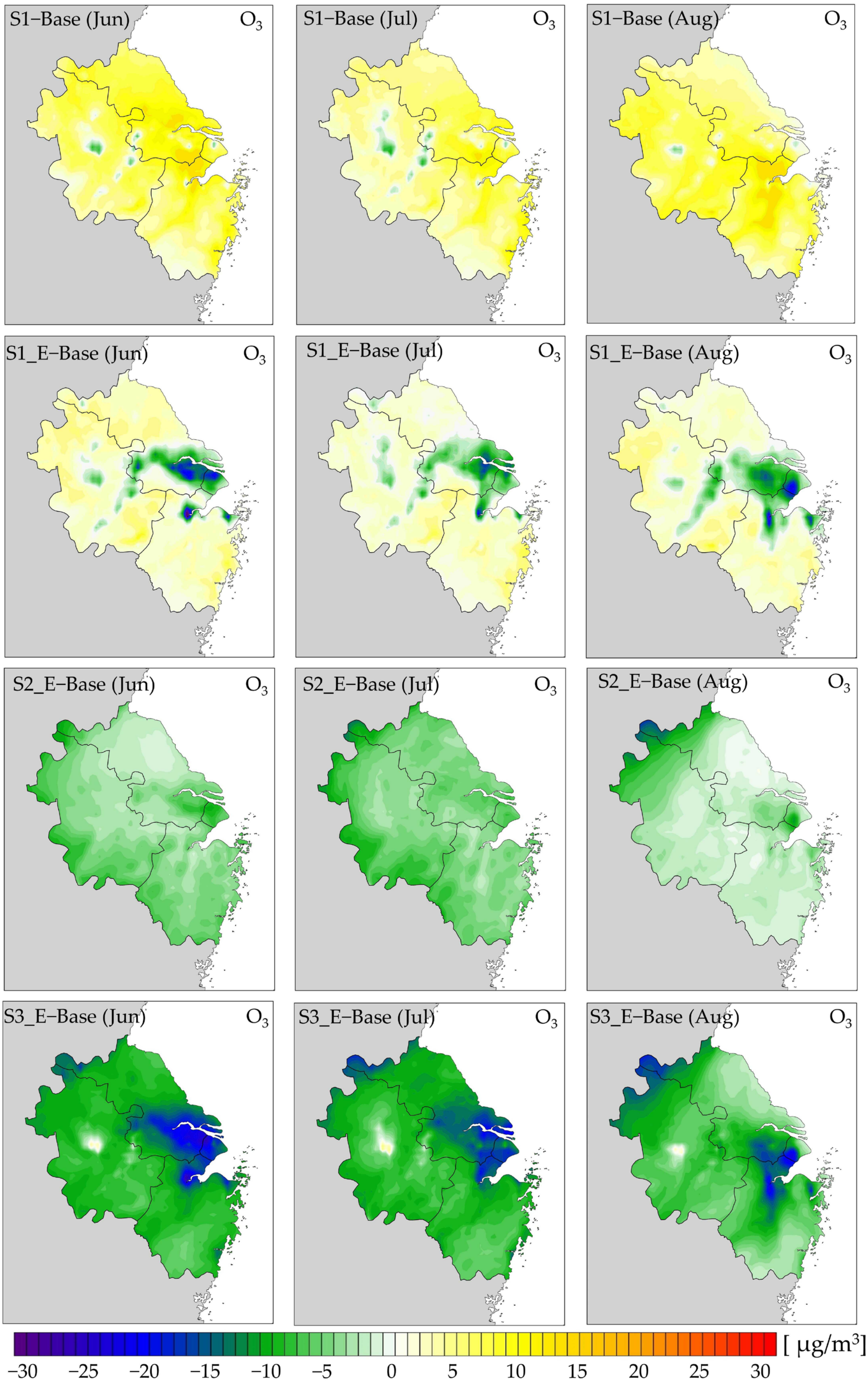

Figure 4. Spatial distributions of monthly average O_3 concentration change values under the 4 control scenarios relative to the base case over the YRD region in June (Jun), July (Jul) and August (Aug), 2025.

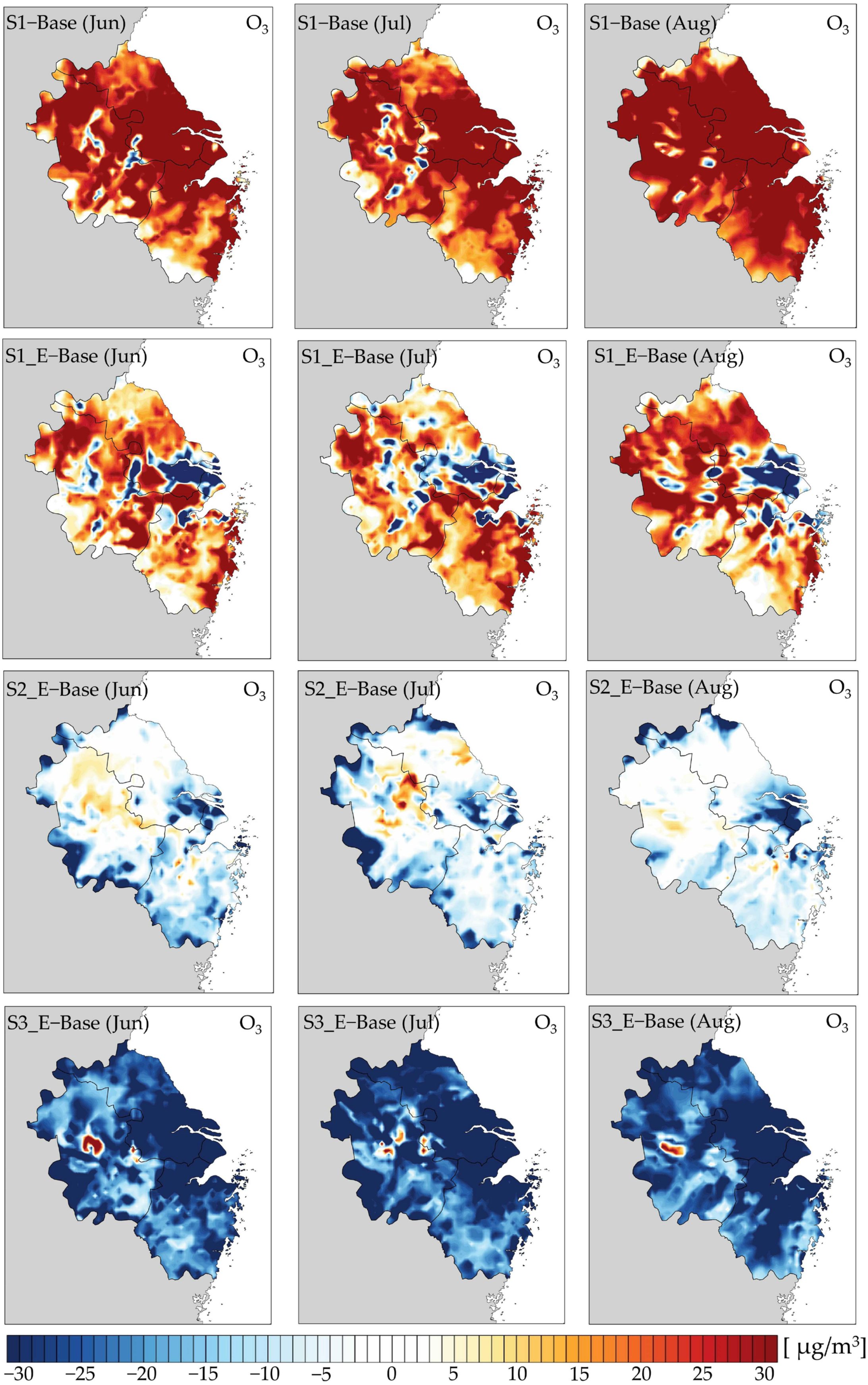

Figure 5. Spatial distributions of MDA8 O_3 concentration change values under the 4 control scenarios relative to the base case over the YRD region in June (Jun), July (Jul) and August (Aug), 2025.

Table 4. Predicted average change values of summer O_3 concentrations under the 6 control scenarios relative to the baseline in 41 main cities of YRD in 2025. The results of the base case are also summarized.

		Base	S1-Base	S1_E-Base	S2_E-Base	S3_E-Base	S2_E_NT-Base	S3_E_NT-Base
Province	City	Concentrations ($\mu g/m^3$)	Change Values ($\mu g/m^3$)					
municipal	Shanghai	93.2 ± 65.9	5.5 ± 12.5	0.6 ± 10.6	−10.2 ± 11.8	−15.5 ± 16.3	−20.8 ± 36.6	−16.2 ± 38.3
Anhui	Anqing	106.6 ± 64.3	6.2 ± 12.8	−14 ± 39.1	−7.1 ± 9.5	−11.3 ± 13.3	−12.4 ± 25.0	−21.1 ± 32.0
	BengBu	94.5 ± 66.1	8.3 ± 16.4	−5.6 ± 24.3	−7.8 ± 9.3	−14.9 ± 16.2	−10.0 ± 28.1	−23.1 ± 34.8
	Bozhou	94.7 ± 62.8	3.8 ± 8.2	−0.6 ± 10.8	−5.8 ± 6.7	−14.6 ± 18.7	0.0 ± 13.8	−35.4 ± 43.8
	Chizhou	94.1 ± 55.6	6.0 ± 12.5	−9.7 ± 22.2	−10.6 ± 10.6	−16.5 ± 31.8	−7.6 ± 24.8	−20.9 ± 51.2
	Chuzhou	104.5 ± 67.4	7.2 ± 15.0	−2.7 ± 13.0	−6.1 ± 6.9	−14.6 ± 17.8	1.6 ± 20.3	−23.0 ± 36.0
	Fuyang	102.2 ± 63.4	3.3 ± 13.3	−1.3 ± 10.1	−8.9 ± 7.5	−13.9 ± 17.8	−7.0 ± 17.4	−19.9 ± 42.6
	Hefei	112.5 ± 69.3	4.9 ± 14.0	3.3 ± 10.0	−8.9 ± 10.0	−11.4 ± 19.0	−1.3 ± 12.1	−25.9 ± 40.5
	Huaibei	97.4 ± 56.9	5.4 ± 13.7	−4.1 ± 18.2	−7.9 ± 8.5	−12.8 ± 15.8	−10.0 ± 22.4	−14.4 ± 28.3
	Huainan	75.1 ± 48.5	6.2 ± 15.0	−7.1 ± 19.5	−7.6 ± 7.1	−17.3 ± 17.3	−2.6 ± 16.9	−16.2 ± 30.9
	Huangshan	76.3 ± 53.6	6.0 ± 16.6	−4.6 ± 17.6	−8.5 ± 9.8	−10.8 ± 12.6	−9.6 ± 27.2	−12.8 ± 26.3
	Luan	96.2 ± 55.7	6.8 ± 17.0	−6.3 ± 16.9	−8.6 ± 9.8	−14.0 ± 19.7	−5.3 ± 20.1	−14.1 ± 26.4
	Maanshan	85.5 ± 52.6	6.3 ± 19.6	0.0 ± 10.4	−7.3 ± 6.6	−10.7 ± 12.2	−8.0 ± 24.1	−4.9 ± 21.8
	Suzhou	102.4 ± 77.6	2.3 ± 12.6	2.6 ± 7.9	−6.7 ± 7.6	−13.0 ± 8.8	−11.8 ± 30.0	−5.7 ± 17.5
	Tongling	107.5 ± 69.0	4.9 ± 13.2	1.6 ± 7.2	−8.0 ± 8.6	−12.1 ± 17.9	−13.6 ± 24.8	−10.1 ± 26.3
	Wuhu	89.7 ± 65.7	7.1 ± 14.3	4.6 ± 10.2	−7.2 ± 8.5	−17.9 ± 22.5	−9.3 ± 21.7	−28.8 ± 40.8
	Xuancheng	87.3 ± 63.0	1.7 ± 14.5	−2.9 ± 15.9	−6.2 ± 5.4	−16.5 ± 19.9	2.3 ± 20.0	−21.1 ± 41.1
Jiangsu	Changzhou	103.3 ± 61.8	5.1 ± 11.1	−7.1 ± 19.6	−7.4 ± 7.5	−10 ± 9.2	−1.6 ± 20.6	−2.1 ± 16.1
	Huaian	102.4 ± 64.9	3.7 ± 11.2	−2.3 ± 17.7	−6.1 ± 7.5	−14 ± 17.6	−3.7 ± 22.2	−27.6 ± 42.6
	Lianyungang	103.9 ± 50.4	5.0 ± 14.1	−6.7 ± 19.9	−9.5 ± 13.2	−17.5 ± 20.7	−8.2 ± 25.4	−15.8 ± 32.6
	Nanjing	94.3 ± 53.3	5.9 ± 14.2	1.3 ± 12.3	−7.1 ± 8.8	−10.6 ± 7.4	−7.3 ± 23.0	−3.6 ± 8.5
	Nantong	96.2 ± 71.0	3.3 ± 12.7	−3.6 ± 17.0	−6.4 ± 7.0	−14.2 ± 13.5	−12.8 ± 25.3	−13.9 ± 34.9
	Suqian	126.3 ± 57.7	6.4 ± 13.1	−8.2 ± 21.7	−7.7 ± 8.1	−13.4 ± 9.4	−17.4 ± 29.2	−9.3 ± 19.6
	Suzhou	99.5 ± 63.8	6.5 ± 15.6	−7.4 ± 17.0	−7.8 ± 11.3	−13.1 ± 13.3	−0.6 ± 24.9	−16.9 ± 29.2
	Taizhou	114.6 ± 67.8	7.5 ± 11.4	−3.4 ± 15.2	−7.4 ± 8.0	−12.5 ± 17.7	−13.9 ± 28.2	−13.7 ± 39.4
	Wuxi	97.6 ± 49.6	7.5 ± 10.4	−9.3 ± 31.6	−6.4 ± 8.1	−16.9 ± 20.7	−11.2 ± 28.9	−25.4 ± 38.0
	Xuzhou	83.1 ± 52.2	10.1 ± 16.3	−2.0 ± 14.5	−8.2 ± 9.7	−12 ± 11.2	−11.5 ± 34.4	−9.1 ± 20.5
	Yangzhou	94.2 ± 59.2	6.6 ± 12.9	−2.6 ± 13.9	−5.5 ± 6.6	−14.7 ± 14.4	1.8 ± 22.0	−9.7 ± 33.3
	Yancheng	123.4 ± 58.2	7.8 ± 15.9	−0.9 ± 16.5	−7.9 ± 7.3	−13.5 ± 17.6	−5.8 ± 20.9	−15.8 ± 36.8
	Zhenjiang	104.5 ± 59.3	6.8 ± 18.7	2.7 ± 9.5	−5.5 ± 6.6	−13 ± 15.3	−10.7 ± 28.2	−16.2 ± 30.5
Zhejiang	Hangzhou	108.4 ± 60.0	2.3 ± 16.3	0.7 ± 8.3	−6.6 ± 7.2	−12.8 ± 16.4	−9.5 ± 21.3	−14.7 ± 38.3
	Huzhou	89.5 ± 48.1	2.6 ± 11.4	−3.5 ± 15.2	−6.4 ± 7.0	−11.4 ± 12.1	−10.5 ± 24.0	−5.2 ± 21.8
	Jiaxing	115.8 ± 64.7	5.7 ± 14.1	−0.9 ± 14.7	−5.3 ± 8.3	−11.6 ± 13.0	0.1 ± 17.9	−9.5 ± 30.4
	Jinhua	98.6 ± 62.3	4.1 ± 19.0	3.3 ± 13.5	−5.6 ± 6.9	−14.7 ± 14.2	−4.2 ± 31.0	−10.9 ± 25.9
	Lishui	78.5 ± 55.2	8.3 ± 16.8	−2.3 ± 19.0	−6.6 ± 8.6	−14.5 ± 9.2	−16.7 ± 32.6	−7.8 ± 20.0
	Ningbo	96.3 ± 57.7	6.4 ± 15.4	−4.6 ± 24.0	−7.8 ± 9.7	−11.6 ± 12.7	−13.7 ± 29.6	−20.9 ± 30.3
	Quzhou	102.4 ± 67.7	7.1 ± 9.5	−5.7 ± 17.9	−10.7 ± 12.6	−15.9 ± 20.9	−7.6 ± 25.4	−12.8 ± 39.9
	Shaoxing	94.3 ± 57.7	7.9 ± 15.6	−7.5 ± 17.3	−5.7 ± 6.3	−17.7 ± 23.2	−10.2 ± 24.8	−17.1 ± 39.3
	Taizhou	127.1 ± 70.5	8.7 ± 14.0	−9.6 ± 21.4	−10.6 ± 13.3	−10.8 ± 8.5	−0.3 ± 19.7	−6.6 ± 18.1
	Wenzhou	85.8 ± 60.9	2.6 ± 11.3	0.8 ± 9.5	−7.6 ± 7.8	−14.0 ± 13.2	−6.9 ± 19.1	−18.1 ± 27.4
	Zhoushan	98.8 ± 55.2	5.2 ± 9.9	1.5 ± 7.1	−5.9 ± 8.2	−12.5 ± 24.5	−6.5 ± 21.6	−22.2 ± 37.9

Table 5. Predicted average change values of summer MDA8 O_3 concentrations under the 6 control scenarios relative to the baseline in 41 main cities of YRD in 2025. The results of the base case are also summarized.

		Base	S1Base	S1_E-Base	S2_E-Base	S3_E-Base	S2_E_NT-Base	S3_E_NT-Base
Province	City	Concentrations ($\mu g/m^3$)	Change Values ($\mu g/m^3$)					
municipal	Shanghai	95.7 ± 64.3	20.2 ± 19.6	2.0 ± 9.5	−5.7 ± 6.4	−18.2 ± 9.3	−2.2 ± 24.8	2.6 ± 21.2
Anhui	Anqing	96.5 ± 51.9	9.7 ± 17.3	−2.7 ± 18.8	−6.5 ± 7.7	−18.2 ± 9.8	6.2 ± 33.2	−0.5 ± 14.5
	BengBu	97.8 ± 38.9	11.1 ± 15.0	−17.3 ± 31.0	−10.6 ± 12.8	−17.2 ± 18.6	−5.4 ± 38.0	−36.5 ± 42.3
	Bozhou	101.2 ± 67.0	14.8 ± 21.3	8.5 ± 8.7	−5.8 ± 5.4	−23.7 ± 16.2	1.2 ± 23.9	−12.6 ± 37.3
	Chizhou	75.0 ± 45.3	10.8 ± 11.6	−16.2 ± 27.3	−7.7 ± 7.3	−27.6 ± 20.9	−0.4 ± 28.5	−12.3 ± 46.4
	Chuzhou	107.8 ± 53.7	10.2 ± 13.6	3.2 ± 8.0	−6.5 ± 7.4	−19.5 ± 22.9	−5.9 ± 27.8	−16.5 ± 34.2
	Fuyang	96.7 ± 55.4	15.9 ± 19.4	4.8 ± 9.1	−9.3 ± 12.1	−21.7 ± 10.1	−3.3 ± 30.3	1.0 ± 16.8
	Hefei	95.6 ± 58.5	13.1 ± 16.5	−2.0 ± 21.9	−7.1 ± 7.0	−30.1 ± 21.7	−10.5 ± 29.7	−16.0 ± 39.8
	Huaibei	73.3 ± 45.6	12.4 ± 15.3	−2.0 ± 17.3	−8.8 ± 9.9	−38.1 ± 21.4	−22.4 ± 35.6	−43.3 ± 63.6
	Huainan	66.8 ± 32.9	18.8 ± 17.3	−2.6 ± 31.0	−7.0 ± 8.7	−35.1 ± 42.1	17.0 ± 24.9	−34.2 ± 74.5
	Huangshan	121.6 ± 51.5	14.5 ± 15.1	−7.7 ± 23.9	−9.0 ± 8.0	−23.5 ± 19.3	−0.4 ± 21.3	−17.9 ± 44.9
	Luan	126.5 ± 58.5	8.9 ± 8.4	5.8 ± 10.4	−8.3 ± 7.8	−28.0 ± 20.6	−2.6 ± 24.5	−19.5 ± 53.8
	Maanshan	97.8 ± 71.2	17.7 ± 14.8	4.5 ± 16.5	−10.0 ± 8.8	−17.8 ± 11.1	−3.9 ± 25.1	−0.9 ± 12.9
	Suzhou	98.4 ± 52.0	10.0 ± 12.6	−4.3 ± 32.8	−10.5 ± 16.4	−27.8 ± 18.6	9.2 ± 19.3	−22.4 ± 44.2
	Tongling	87.2 ± 53.8	15.2 ± 19.9	−7.8 ± 22.3	−11.5 ± 9.0	−14.9 ± 10.1	−11.0 ± 19.6	−18.1 ± 30.8
	Wuhu	86.9 ± 70.2	18.5 ± 19.8	−0.1 ± 20.8	−7.0 ± 8.3	−18.0 ± 15.4	3.5 ± 43.1	−16.1 ± 31.3
	Xuancheng	92.4 ± 68.4	16.2 ± 18.1	−1.8 ± 23.5	−11.1 ± 11.6	−20.9 ± 8.9	1.1 ± 26.8	−20.3 ± 32.7

Table 5. *Cont.*

		Base	S1Base	S1_E-Base	S2_E-Base	S3_E-Base	S2_E_NT-Base	S3_E_NT-Base
Province	**City**	**Concentrations ($\mu g/m^3$)**	**Change Values ($\mu g/m^3$)**					
Jiangsu	Changzhou	90.2 ± 62.7	11 ± 10.7	−15 ± 29.0	−15.0 ± 14.0	−16.2 ± 7.1	−11.9 ± 38.7	0.9 ± 13.4
	Huaian	105.1 ± 59.7	8.7 ± 13.0	−11.4 ± 34.6	−6.2 ± 7.6	−22.7 ± 10.4	12.9 ± 24.0	4.8 ± 30.0
	Lianyungang	109.4 ± 57.7	7.8 ± 14.6	−1.7 ± 22.1	−7.9 ± 6.7	−22.0 ± 10.6	−16.0 ± 31.4	−19.4 ± 31.2
	Nanjing	86.9 ± 30.3	7.8 ± 7.7	−14.4 ± 30.8	−5.9 ± 6.3	−19.5 ± 12.8	−4.5 ± 31.1	−28.1 ± 37.4
	Nantong	101.8 ± 59.2	11.8 ± 20.4	9.4 ± 15.1	−10.0 ± 7.9	−21.2 ± 18	−10.1 ± 29.7	−15.0 ± 40.6
	Suqian	85.6 ± 56.7	16.2 ± 16.0	9.1 ± 9.9	−7.6 ± 8.9	−38.0 ± 31.8	3.7 ± 16.7	−29.5 ± 52.8
	Suzhou	91.3 ± 38.2	8.9 ± 17.7	−3.5 ± 13.7	−12.5 ± 8.8	−28.4 ± 28.2	−14.4 ± 38.4	−1.6 ± 54.2
	Taizhou	93.0 ± 65.5	15.0 ± 17.0	12.9 ± 9.6	−8.2 ± 9.1	−16.6 ± 10.2	−18.6 ± 35.1	−2.1 ± 13.2
	Wuxi	95.8 ± 58.8	16.7 ± 17.3	−0.4 ± 13.9	−6.7 ± 7.7	−32.1 ± 22.4	12.3 ± 19.5	−41.1 ± 53.2
	Xuzhou	90.7 ± 71.1	10.1 ± 11.2	3.3 ± 13.8	−8.1 ± 8.4	−16.7 ± 17.6	3.5 ± 37.9	3.7 ± 26.1
	Yangzhou	88.0 ± 37.1	11.1 ± 16.2	−2.6 ± 20.6	−8.6 ± 9.2	−18.1 ± 10.5	11.8 ± 31.7	2.8 ± 23.9
	Yancheng	124.6 ± 57.5	11.5 ± 8.6	2.5 ± 8.4	−13.4 ± 10.4	−18.9 ± 9.5	10.8 ± 21.7	−7.9 ± 31.1
	Zhenjiang	72.5 ± 34.3	11.4 ± 11.3	10.8 ± 9.1	−7.8 ± 11.0	−23.6 ± 13.7	5.8 ± 18.4	−4.2 ± 26.6
Zhejiang	Hangzhou	69.5 ± 25.3	12.6 ± 11.2	−3.7 ± 18.1	−8.5 ± 10.5	−19.2 ± 11.2	−0.1 ± 30.9	2.9 ± 29.7
	Huzhou	89.6 ± 37.6	17.2 ± 14.2	3.9 ± 13.6	−7.1 ± 5.9	−18.9 ± 15.7	−6.7 ± 32.8	−31.2 ± 41.5
	Jiaxing	85.5 ± 57.6	11.8 ± 16.1	−32.1 ± 55.5	−12.8 ± 11.6	−22.2 ± 13.0	−23.1 ± 34.5	−12.5 ± 36.3
	Jinhua	77.4 ± 60.6	13.2 ± 16.3	−7.6 ± 22.9	−14.4 ± 9.8	−26.1 ± 29.4	−17.2 ± 44.2	−54.0 ± 48.3
	Lishui	103.2 ± 71.0	6.1 ± 14.3	2.8 ± 11.9	−6.1 ± 6.9	−38.3 ± 26.2	1.0 ± 25.0	−45.2 ± 45.7
	Ningbo	79.4 ± 35.8	12.5 ± 12.4	0.9 ± 16.2	−7.5 ± 6.8	−24.9 ± 15.9	−4.6 ± 26.0	−13.6 ± 32.8
	Quzhou	66.8 ± 23.2	12.2 ± 14.1	−1.1 ± 21.2	−9.8 ± 12.5	−26.3 ± 23.7	−17.4 ± 49.0	−34.3 ± 48.7
	Shaoxing	92.5 ± 58.9	9.4 ± 14.7	−1.2 ± 16.4	−5.3 ± 7.8	−28.5 ± 28.0	−1.5 ± 45.4	−25.2 ± 56.4
	Taizhou	135.9 ± 63.9	14.1 ± 12.7	−12.1 ± 39.8	−14.4 ± 11.9	−19.6 ± 14.0	−6.0 ± 19.6	−13.7 ± 41.3
	Wenzhou	90.6 ± 68.0	8.7 ± 13.4	10.0 ± 12.3	−5.9 ± 8.1	−28.4 ± 19.3	6.4 ± 25.0	−30.7 ± 53.7
	Zhoushan	127.9 ± 58.2	13.8 ± 16.6	0.4 ± 17.9	−7.0 ± 7.5	−31.5 ± 22.0	10.7 ± 22.4	−22.0 ± 42.2

Under the S1_E scenario, the emission reduction effects of NOx and VOCs on O_3 were enhanced with improvements in the O_3 control efficiency (Figure 4), in which O_3 concentrations in the central areas of the middle and lower reaches of the YRD slightly decreased due to the increases in VOCs emission reduction proportions. It is worth noting that under the S1 scenario, the emission reduction rates for NOx and VOCs were close, while under the S1_E scenario the emission reduction rates for VOCs were higher than those for NOx. The rising trends of O_3 concentrations in the YRD under the S1 scenario were alleviated under the S1_E scenario in which there were downward trends for the O_3 concentrations in Shanghai, central and Northern Anhui, Central Jiangsu and Northern Zhejiang. In the summer of 2025, the averages of city mean O_3 concentrations of the 3 summer months in the YRD under the S1_E scenario were predicted to slightly decrease with the maximum values of -14 $\mu g/m^3$ (in Anqing city), -9.3 $\mu g/m^3$ (in Wuxi city), and -9.6 $\mu g/m^3$ (in Taizhou city) in Anhui, Jiangsu, and Zhejiang, respectively (see Table 4). The downward trends were more evident in spatial distributions of monthly mean MDA8 O_3 concentrations (Figure 5). It is predicted that the means of city MDA8 O_3 concentrations of the 3 summer months of 2025 will have the maximum decrease values of -17.3 $\mu g/m^3$ (in Bengbu city), -15.0 $\mu g/m^3$ (in Changzhou city), and -32.1 $\mu g/m^3$ (in Jiaxing city) $\mu g/m^3$ in Anhui, Jiangsu, and Zhejiang, respectively (see Table 5). This indicates that emission reduction policies for VOCs were more effective in influencing serious O_3 pollution. As pointed out by Simon et al. [54], NO_x participated in competing O_3 creation and destruction reactions, and the response of O_3 concentrations to changes in NOx or VOC emissions relies on their relative concentrations and the intensity of insolation. The effects of NO_x are mainly O_3 destruction under the condition that either the VOC/NOx ratios are low or insolation is very low (VOC or oxidant limited condition). This means that in the regions with elevated NO_x concentrations due to high emissions densities (e.g., urban centers with significant traffic), reductions in NOx will lead to increases in local ozone concentrations. On the other hand, under the condition that the VOC/NO_x ratios are high (NOx limited conditions), the main effects of NOx are O_3 formation, and reductions in NO_x will lead to decreases in local O_3 concentrations [54]. The increasing trends of O_3 concentrations in the most areas of the YRD with the decreases in precursor emissions under the S1 scenario in Table 4 indicate the VOC limited conditions for the O_3 formation. On the other hand, the S1_E scenario under which the emission reduction rates for VOCs were higher than those for NO_x compared to the S1 scenario shows decreasing trends for the O_3 concentrations in Shanghai, central and Northern Anhui, Central Jiangsu and Northern Zhejiang (Figure 5), indicating the NO_x limited conditions. In summary, the spatial variations of O_3 responses to the emission controls under the S1 and S1_E scenarios show that different emission reduction rates for VOCs and NOx may lead to different control effects of O_3 in the YRD.

The spatial distributions of O_3 change values under the S2_E and S3_E scenarios relative to the base case in Figures 4 and 5 revealed that the decreases in city hourly and MDA8 O_3 mean concentrations in almost all the cities in YRD were found by controlling high-emission industries. Under the S2_E scenario, the maximum decreases in city mean O_3 concentrations in Shanghai, Anhui, Jiangsu and Zhejiang were predicted to be -12.2 μg/m^3 (in July in Shanghai city), -14.3 μg/m^3 (in July in Hefei city), -15.8 μg/m^3 (in July in Suzhou city), and -17.6 μg/m^3 (in July in Taizhou city) μg/m^3, respectively (see Tables S6–S8). Under the S2_E scenario, the average decrease values of MDA8 O_3 concentrations in Anhui, Jiangsu and Zhejiang were -24.5 μg/m^3 (in June in Suzhou city), -26.3 μg/m^3 (in August in Changzhou city), and -18.2 μg/m^3 (in July in Jinhua city) μg/m^3, respectively (see Tables S9–S11). The higher O_3 concentration abatements were found under the S3_E scenario relative to the S2_E scenario as shown in Figures 4 and 5. In general, the largest drops of ozone concentrations were predicted under the S3_E scenario because of its highest control strength of precursors. The maximum average decrease values of city mean MDA8 O_3 concentrations were -69.7 μg/m^3 (in August in Huainan city) in Anhui, followed by -52 μg/m^3 (in June in Suqian city) in Jiangsu, -51.2 μg/m^3 (in July in Lishui city) in Zhejiang, and -19.6 μg/m^3 (in July) in Shanghai under the S3_E scenario relative to the base case (see Tables S9–S11). It is noteworthy that the S2_E and S3_E scenarios gained more decreases in city mean MDA8 O_3 concentration decreases than those for hourly O_3 concentrations.

It was found that O_3 concentrations in most areas of the YRD region increased under the S2_E_NT and S3_E_NT scenarios without transportation emissions (see Figures S5 and S6). The MAD8 O_3 levels in most areas of the Yangtze River Delta showed an upward trend under the S2_E_NT scenario relative the base case. As shown in Figure S6, the areas with elevated MDA8 O_3 concentrations were mainly located in the central parts of Northern Anhui and Zhejiang and most areas of Jiangsu and Shanghai. The maximum monthly average increases in MAD8 O_3 concentrations in the 3 summer months under the S2_E_NT scenarios were 12.3 μg/m^3 (in June in Shanghai), 28.8 μg/m^3 (in July in Huainan city), 23.3 μg/m^3 (in July in Wuxi city) and 33.5 μg/m^3 (in June in Quzhou city) in Shanghai, Anhui, Jiangsu, Zhejiang, respectively (see Tables S9–S11). However, in the areas where O_3 concentrations decreased under the S1 scenarios, a greater decrease in ozone under the enhanced scenarios will be expected.

4. Conclusions

This study used the WRF/CMAQ model to explore the potential impacts of emission control policies for Chinese 14th FYP on $PM_{2.5}$ and O_3 in Yangtze River Delta, China, and aimed to provide a scientific basis for the controls of $PM_{2.5}$ and O_3 in the future. The simulation results of the 4 emission control scenarios in the 2 winter months in 2025 indicate that under both S1 and S1_E scenarios, the average concentrations of city mean $PM_{2.5}$ in 41 cities in the YRD were predicted to decrease only by 10%, whereas the enhanced emission control scenarios (i.e., S2_E and S3_E) were predicted to reduce $PM_{2.5}$ in each city by more than 20%, thus being able to meet the targets of air quality improvements in 2025 promised by the government. For example, under the S3_E (S1_E) scenario, the monthly average concentrations of city mean $PM_{2.5}$ were predicted to decrease by -19.0 μg/m^3 in Chizhou city of Anhui province (-7.6 μg/m^3 in Anqing city of Anhui province), followed by -16.5 μg/m^3 in Hangzhou of Zhejang province (-5.8 μg/m^3 in Ningbo city of Zhejiang province), -15.6 μg/m^3 in Suzhou city of Jiangsu province (-5.4 μg/m^3 in Zhenjiang city of Jiangsu province), and -10.7 μg/m^3 in Shanghai (-1.4 μg/m^3 in Shanghai) in December (see Table S4). The model simulation results for O_3 in the 3 summer months in 2025 show that the O_3 responses to the emission controls under the S1 and S1_E scenarios show different control effects on O_3 concentrations in the YRD with the increase and decrease effects, respectively, although both cannot achieve the control target for O_3. The model results also reveal that both enhanced emission control scenarios (S2_E and S3_E) were predicted to decrease O_3 in each city by more than 20% with more reductions in O_3 under the S3_E emission control scenario because of its higher control strength of both NOx and VOCs, being able to meet the targets of air quality improvements in 2025 promised by the government. This result indicates that if the 14th FYP adopted the same emission control scenarios in the 13th FYP, its effectiveness and compliance would not achieve the targets of air quality improvements in the YRD by 2025. The study found that emission reduction policies for controlling high emission sectors of NOx and VOCs such as S2_E and S3_E were more effective for decreasing both $PM_{2.5}$ and O_3 in the YRD. The economic development in China will put heavy demand on the consumption of energy and rapid productivity growth, which result in continuously increasing of precursor emissions. Our study found that O_3 controls will benefit from well-designed air pollution control strategies of reasonable control ratios of NOx and VOCs emissions. The reasonable and sustainable emission abatement will ensure the further decline of $PM_{2.5}$ and O_3 in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos13010026/s1, Figure S1: a. The model domain covering China with a horizontal resolution of 12 km × 12 km and 345 × 395 grid cells. b. The Yangtze River Delta region and districts of Shanghai, Anhui, Jiangsu, and Zhejiang. c. Map of Yangtze River Delta region with marked location of each city; Figure S2: Monthly mean concentrations of $PM_{2.5}$ in Yangtze River Delta urban agglomerations in recent 6 years; Figure S3: Monthly mean concentrations of O_3 in Yangtze River Delta urban agglomerations in recent 6 years; Figure S4: Spatial distributions of $PM_{2.5}$ concentration decrease percentages under the four control scenarios relative to the baseline over the Yangtze River Delta region in January and December, 2025; Figure S5: Spatial distributions of decrease values of monthly average O_3 concentrations under the four control scenarios relative to the baseline over the Yangtze River Delta region in June, July and August, 2025; Figure S6: Spatial distributions of decrease values of MDA8 O3 concentrations under the four control scenarios relative to the baseline over the Yangtze River Delta region in June, July and August, 2025. Table S1: Definitions of emission sectors in the inventory; Table S2: Annual emissions for each sector species of each province in YRD (tons/year); Table S3: List of cities in YRD and the abbreviations of city name used in this study; Table S4: Predicted decrease values of $PM_{2.5}$ concentrations under the four control scenarios relative to the baseline case in 41 main cities of YRD in December, 2025. Table S5: Predicted decrease values of $PM_{2.5}$ concentrations under the four control scenarios relative to the baseline case in 41 main cities of YRD in January, 2025; Table S6: Predicted decrease values of O_3 concentrations under the six control scenarios relative to the baseline case in 41 main cities of YRD in June, 2025; Table S7: Predicted decrease values of O_3 concentrations under the six control scenarios relative to the baseline case in 41 main cities of YRD in July, 2025; Table S8: Predicted decrease values of O_3 concentrations under the six control scenarios relative to the baseline case in 41 main cities of YRD in August, 2025; Table S9: Predicted decrease values of MDA8 O_3 concentrations under the six control scenarios relative to the baseline case in 41 main cities of YRD in June, 2025; Table S10: Predicted decrease values of MDA8 O_3 concentrations under the six control scenarios relative to the baseline case in 41 main cities of YRD in July, 2025; Table S11: Predicted decrease values of MDA8 O_3 concentrations under the six control scenarios relative to the baseline case in 41 main cities of YRD in August, 2025.

Author Contributions: S.Y. and Z.L. designed this study and wrote the manuscript. Z.L. and S.Y. contributed to observations and data analyses, M.L., X.C., Y.Z., Z.S., J.L., Y.J., W.L., P.L. and X.Z. contributed to the discussions. S.Y. contributed to the manuscript and supervised the research. All authors have read and agreed to the published version of the manuscript.

Funding: This work was partially supported by the National Natural Science Foundation of China (Nos. 42175084, 21577126 and 41561144004),Department of Science and Technology of China (Nos. 2018YFC0213506, 2018YFC0213503, and 2016YFC0202702,), and National Research Program for Key Issues in Air Pollution Control in China (No. DQGG0107). Part of this work was also supported by the “Zhejiang 1000 Talent Plan” and Research Center for Air Pollution and Health in Zhejiang

University. Pengfei Li is supported by National Natural Science Foundation of China (No. 22006030), Initiation Fund for Introducing Talents of Hebei Agricultural University (412201904), and Hebei Youth Top Q15 Fund (BJ2020032).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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