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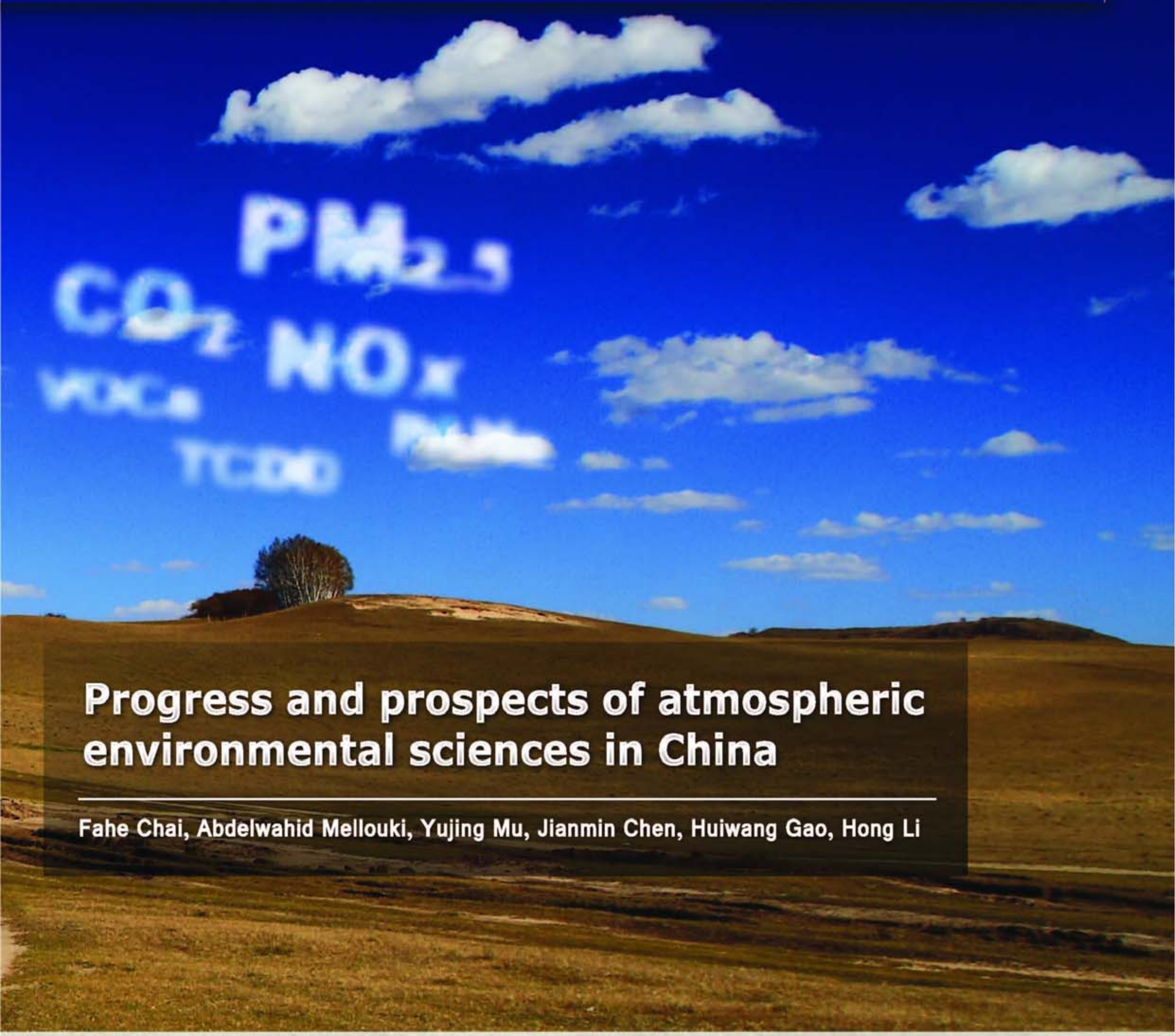

Progress and prospects of atmospheric environmental sciences in China

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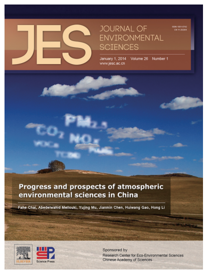

Effectiveness of national air pollution control policies on the air quality in metropolitan areas of China

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ABSTRACT

Understanding the effectiveness of national air pollution controls is important for control policy design to improve the future air quality in China. This study evaluated the effectiveness of major national control policies implemented recently in China through a modeling analysis. The sulfur dioxide (SO_2) control policy during the 11th Five Year Plan period (2006–2010) had succeeded in reducing the national SO_2 emission in 2010 by 14% from its 2005 level, which correspondingly reduced ambient SO_2 and sulfate (SO_4^{2-}) concentrations by 13%–15% and 8%–10% respectively over east China. The nitrogen oxides (NO_x) control policy during the 12th Five Year Plan period (2011–2015) targets the reduction of the national NO_x emission in 2015 by 10% on the basis of 2010. The simulation results suggest that such a reduction in NO_x emission will reduce the ambient nitrogen dioxide (NO_2), nitrate (NO_3^-), 1-hr maxima ozone (O_3) concentrations and total nitrogen deposition by 8%, 3%–14%, 2% and 2%–4%, respectively over east China. The application of new emission standards for power plants will further reduce the NO_2, NO_3^-, 1-hr maxima O_3 concentrations and total nitrogen deposition by 2%–4%, 1%–6%, 0–2% and 1%–2%, respectively. Sensitivity analysis was conducted to evaluate the inter-provincial impacts of emission reduction in Beijing-Tianjin-Hebei and the Yangtze River Delta, which indicated the need to implement joint regional air pollution control.

Introduction

Recent studies indicate that the status of air pollution in China is far more complicated than ever before (Shao et al., 2006; Hao et al., 2007; Chan and Yao, 2008; Wang and Hao, 2012). With the rapid development of the economy, urbanization and transportation, almost all types of air pollution problems, which were experienced for nearly a century in developed countries, exploded in China within last two decades. Complex air pollution, characterized by regional photochemical smog and haze, exhibited an increasing trend in recent years in rapidly developing regions such as the North China Plain (NCP), the Yangtze River Delta (YRD) and the Pearl River Delta (PRD). In order to prevent the further deterioration of air quality and to protect human health and the ecosystem, the Chinese government has implemented a series of national control policies to reduce the emissions of air pollutants since 2005 (Wang and Hao, 2012). The 11th Five-Year Plan (FYP) (2006–2010) for national environmental protection required the reduction of annual emissions of sulfur dioxide (SO_2) in 2010 by 10% from its 2005 level. To achieve this goal, flue gas desulfurization (FGD) has been widely installed in coal-fired power plants. In 2005, only 15% installed capacity of power plants had FGD, but the

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percentage had increased to 81% by 2010 (Xing et al., 2011a). Consequently, the national trend of SO_2 emissions turned to a decrease after two-decade growth. A large reduction in ambient SO_2 level has been also observed by ground monitors and satellite monitoring instruments (Wang and Hao, 2012; Li et al., 2010).

Urgent needs for nitrogen oxide (NO_x) control in China have been addressed in recent studies (Zhao et al., 2009; Li et al., 2013). In China's 12th FYP (2011–2015), nationwide controls on NO_x emission will be implemented along with the controls on SO_2 and primary particles. The Ministry of Environmental Protection (MEP) of China set a target to reduce the national NO_x emissions in 2015 by 10% from the 2010 level. Nationwide control actions involving all newly-built and most existing power plants, iron and steel plants, cement plants and vehicles are being taken. In addition, on 29 July in 2011, MEP released a new "emission standard of air pollutants for thermal power plants" (GB 13223-2011) to further strengthen the NO_x controls and guarantee the achievement of the 12th FYP target.

Regional air pollution has drawn more and more attention in China. For metropolitan areas in particular, the cities within regions suffer significant interactive impacts from each other. In order to better improve the regional air quality throughout metropolitan areas, MEP has issued the action of "Joint Prevention and Control of Air Pollution" in 2011, which will first be implemented in three key regions, i.e., the Beijing-Tianjin-Hebei Region, YRD and PRD during the period of the 12th FYP. This plan aims to establish a joint prevention and control system and ensure that all cities in the three key regions maintain air quality at or better than the Grade II National Ambient Air Quality Standard (GB 3095–1996) and effectively improve the regional air quality.

Currently China is at the most critical stage of air quality management. Evaluation of the current and future policies' effectiveness is not only important for our understanding of the role of current national control policy but also vital for future policy design. Following our previous studies (Wang et al., 2010a, 2010b; Wang and Hao, 2012), this article used the Model-3/Community Multi-scale Air Quality Model (CMAQ) to analyze the effectiveness of national air pollution control policies implemented recently in China. Besides the baseline, several hypothetical scenarios with different emissions have been simulated. From the sensitivity analysis, the control effectiveness of the 11th FYP on SO_2 and 12th FYP on NO_x has been evaluated. The necessity of regional joint control action is addressed as well.

1 Methodology

1.1 Emission inventories

Following the same methodology as Wang et al. (2011a), the emission inventories in 2010 and 2015 were updated from our previous emission inventory in 2005 according to the changes in activities and implementation of control measures. The activity growth was calculated using the method developed by Xing et al. (2011a) and Zhao et al. (2013a). Key parameters used for the emission prediction are given in **Table 1**. Details on the description of each scenario are given in **Table 2**.

The 2005 reference scenario (REF) represents the SO_2 and NO_x emissions in 2005. The 2010 business-as-usual scenario (BAU) assumed that there were no controls on SO_2 emissions during the 11th FYP. The 2010 baseline scenario (BAS) considered the SO_2 emission control policies by sector during the 11th FYP, as seen in **Table 2**. The national anthropogenic emissions of SO_2, NO_x, particles with aerodynamic diameter less than 10 μm (PM_{10}) and non-methane volatile organic compounds (NMVOC) in 2010 are estimated to be 24.6 Tg, 24.9 Tg, 11.7 Tg and 20.2 Tg, respectively. Compared with 2005, the emissions of SO_2 and PM_{10} in 2010 decreased by 14% and 39%, respectively. However, the emissions of NO_x and NMVOC increased by 34% and 21%, respectively (Zhao et al., 2013b). In order to evaluate the effectiveness of national SO_2 control policy during the period of the 11th FYP, two hypothetical emission scenarios were designed. The difference between BAU and BAS scenarios represents the absolute reduction amount of SO_2 emissions by the 11th FYP control. The difference between REF and BAS represents the relative changes caused by the 11th FYP control compared to 2005.

To evaluate the effectiveness of national NO_x control policy during the current 12th FYP period, three hypothetical emission scenarios were designed. In 2015 BAU, we assumed the NO_x emission will keep on growing without the 12th FYP control. For the other two controlled scenarios, in 2015 FYP we assumed the NO_x control of the 12th FYP applied; in 2015 new standard for power plants scenario (POW) we assumed the new emission standard of power plant applied to further reduce the NO_x emission. Therefore, the difference between FYP and BAU represents the absolute reduction amount of NO_x emission

Table 1 Key parameters used in the prediction of 2015 activities

Item	2005	2010	2015
GDP (2005 price, billion CNY)	18322	31097	45692
Population ($\times 10^6$)	1306	1340	1390
Power generation (TWh)	2500	4207	5579
Crude steel yield (Mt)	353	627	675
Cement yield (Mt)	1069	1880	1940
Urban residential building area per capita (m^2)	19.2	23.0	26.0
Rural residential building area per capita (m^2)	29.7	34.1	36.5

Table 2 Emission scenarios and their corresponding control measures

Year	Name	Power plant (PP)	Industry boiler (IN)	Transportation (TR)	Residential sector (DO)
2005	Reference (REF)	2005 baseline	2005 baseline	2005 baseline	2005 baseline
2010	Business as usual (BAU)	2005 baseline	2005 baseline	2005 baseline	2005 baseline
	Baseline (BAS)	FGD system installed in all new thermal power plants and most existing ones; shut down small plants with low energy efficiency during 11th FYP	Clean combustion technology employed in industries; comprehensive treatment of waste gases	The same as BAU	Clean fuel used in residential sector; concentrated urban heat supply
2015	Business as usual (BAU)	2010 baseline	2010 baseline	2010 baseline	2010 baseline
	12th FYP control (FYP)	LNB used in all coal-fired power plants; flue gas de-NO*x* technology installed in the plants that are 200 MW or larger	LNB applied in newly-built industrial boilers including sinters and the cement plants with the precalcining technique	Applied the new vehicle standard (Euro IV)	Energy saving and clean fuel used in residentialsector; Concentrated urban heat and gas supply
	New emission standard for power plant (POW)	New emission standard implemented for power plant	The same as 12th FYP	The same as 12th FYP	The same as 12th FYP

by the 12th FYP control, and the difference between POW and FYP represents the effectiveness of the stricter emission standard for power plants.

This study only focused on the control on SO_2 and NOx. Emissions for other species are kept the same as 2010 BAS. The comparisons of SO_2 and NOx emission in different scenarios and provinces are given in **Fig. 1** and **Table 3**.

1.2 Air quality modeling system

The air quality model used in this study is the CMAQ modeling system (ver. 4.7.1), developed by the US Environmental Protection Agency. A complete description of CMAQ configuration, meteorological, emission, and initial and boundary condition inputs used for this analysis are described by Wang et al. (2011a). The modeling domain covers most of China with a 36 × 36 km grid resolution, as shown in **Fig. 2**. The three most developed regions over east China (ECH), i.e., NCP, the YRD and the PRD, as well as three megacities, Beijing, Shanghai and Guangzhou located in each region, have been chosen as the target areas and cities. The simulation period is January and July in 2010.

The simulations of this modeling system have been validated through comparison with observations of satellite retrievals and surface monitoring data, in aspects of the NO_2, SO_2 column density and Aerosol Optical Depth, as well as ground concentrations of SO_2, NO_2, PM_{10}, $PM_{2.5}$ and its component.

1.3 Validation of emission reductions using observed SO_2/NO_2 ratio

The changes of SO_2 and NOx emissions may cause a considerable change of SO_2/NO_2 ratio observable in

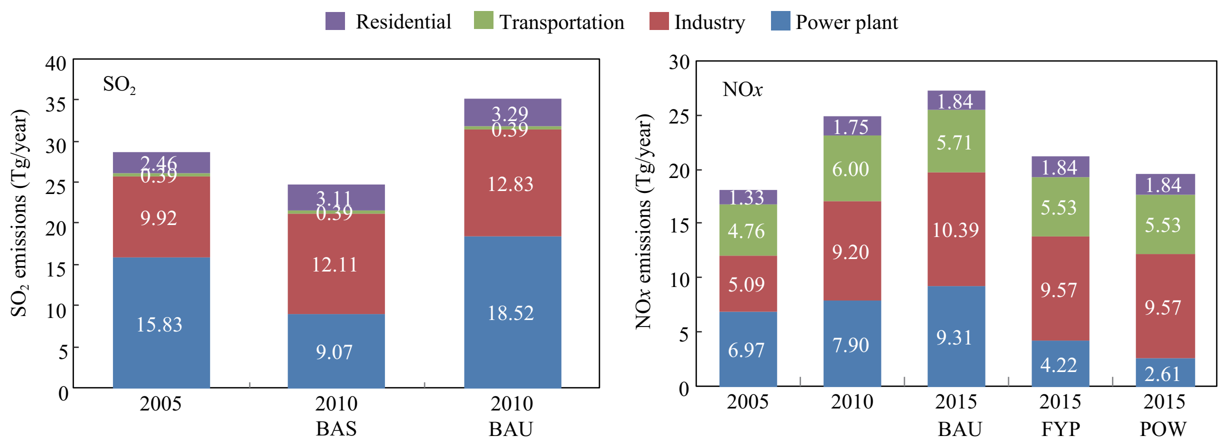


Fig. 1 Comparison of SO_2 and NOx emissions in each scenario.

Table 3 Provincial emissions in each scenario (unit: Gg/year)

	SO_2			NO*x*					PM_{10}	NMVOC
	2005REF	2010BAU	2010BAS	2005REF	2010BAS	2015BAU	2015FYP	2015POW	2010	2010
Anhui	640	786	578	763	943	1039	784	698	502	872
Beijing	213	263	202	316	460	414	348	340	112	362
Chongqing	689	871	715	259	377	400	334	316	209	341
Fujian	437	540	404	384	720	860	675	608	284	476
Gansu	324	394	270	318	425	475	356	312	182	225
Guangdong	1107	1344	912	1155	1664	1825	1341	1284	638	1817
Guangxi	792	985	758	364	528	560	461	433	551	775
Guizhou	1496	1834	1253	416	461	521	386	336	377	393
Hainan	57	68	46	54	90	96	72	64	48	114
Hebei	2377	2921	2112	1468	1728	1918	1480	1434	791	1113
Heilongjiang	293	356	243	574	644	690	538	483	371	558
Henan	1764	2121	1328	1287	1707	1807	1448	1323	781	1157
Hubei	1255	1543	1114	675	826	903	732	683	433	685
Hunan	1012	1259	965	575	780	843	676	625	489	626
Jiangsu	1764	2140	1433	1348	1736	1896	1254	1180	779	1845
Jiangxi	585	712	483	353	532	566	454	420	248	391
Jilin	383	473	348	452	544	571	443	397	281	400
Liaoning	1146	1404	992	808	1061	1139	908	822	528	797
Nei Mongol	978	1188	779	683	1065	1177	803	655	385	421
Ningxia	355	424	253	157	262	303	199	158	85	92
Qinghai	18	23	20	50	87	85	69	65	36	46
Shaanxi	914	1105	700	412	633	701	523	460	240	324
Shandong	3356	4111	2914	1767	2363	2635	2140	1963	930	1884
Shanghai	370	450	305	407	468	522	338	313	150	476
Shanxi	1621	1954	1219	813	1037	1130	840	725	471	489
Sichuan	2025	2515	1898	712	883	925	798	768	621	1274
Tianjin	374	458	327	257	366	387	267	254	142	238
Tibet	1	1	1	15	24	23	21	21	2	13
Xinjiang	309	387	305	286	417	433	359	333	333	338
Yunnan	557	687	505	428	493	500	415	387	276	401
Zhejiang	1385	1714	1297	946	1250	1405	876	819	462	1239
Total	28597	35031	24679	18502	24574	26749	20338	18679	11737	20182

NMVOC: non-methane volatile organic compound.

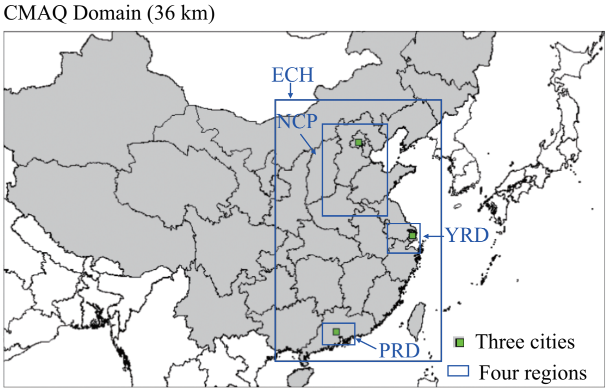


Fig. 2 Modeling domain and location of targeted cities and regions. NCP: North China Plain, YRD: Yangtze River Delta, PRD: Pearl River Delta, ECH: East China.

the environment, such as that in ambient concentrations, aerosol chemical components and wet depositions. Ambient SO_2 and NO_2 concentrations have a relative linear response relative to their primary emissions. Therefore it is possible to validate their emission changes based on the changes of observed NO_2/SO_2 ratios (Li et al., 2010).

In this study, two types of observed SO_2/NO_2 ratio were collected for the period of 2005–2010. First, the daily concentration of SO_2 and NO_2 in three megacities, i.e., Beijing, Shanghai and Guangzhou were derived from the Air Pollution Index reported by local environmental monitoring centers (Wang et al., 2011a). The other is the tropospheric vertical density (VCD) of SO_2 and NO_2 measured by the satellite remote sensors. The monthly NO_2 VCD data is from the Dutch ozone monitoring instrument NO_2 (DOMINO) product by the Royal Netherlands Meteorological Institute (KNMI) (Boersma et al., 2007). The monthly SO_2 VCD data is from the SCIAMACHY product by BIRA-IASB (2008). Details on the data processing are given by Zhao et al. (2013c).

2 Results and discussion

2.1 Impacts of SO_2 emission control during 11th FYP

2.1.1 Reduction in SO_2 and SO_4^{2-} concentrations

From the sensitivity analysis with CMAQ, we compared the simulated SO_2 and SO_4^{2-} concentrations under three emission scenarios. The results are given in **Table 4**.

Based on our results, the 11th FYP control on SO_2 emission benefits the reduction in SO_2 concentrations by 13%–15% compared to 2005 over east China. It also benefits the reduction of the aerosol SO_4^{2-} concentrations by 8%–10% compared to 2005.

In the case of no 11th FYP controls, due to the continual growth of activity, the ambient SO_2 and SO_4^{2-} concentrations would increase by 21%–27% and 12%–17% respectively during the period of 2005–2010.

2.1.2 Changes of SO_2/NO_2 ratio

The simulated NO_2 concentration in 2010 increased by 37% compared to 2005, for both 2010 BAS and BAU scenarios. Combined with the change of SO_2 concentration in BAS, the simulated change in SO_2/NO_2 ratio is calculated to be 37%, which indicates the 11th FYP controls will reduce the SO_2/NO_2 ratio by 37% compared to 2005. In BAU, the SO_2/NO_2 ratio decreases as well, by 11%. That is because the increase of NO*x* emission was faster than that of SO_2 due to higher growth rates of vehicle populations and several industry processes (e.g., cement plants), which contribute more to total emissions of NO*x* than SO_2.

The observed concentrations of SO_2 and NO_2 and the SO_2/NO_2 ratio are given in **Fig. 3**. As seen from satellite retrievals over the three key regions, the SO_2 VCD present obvious decreases since 2007 (2006 for PRD). The SO_2 VCD over east China in 2010 decreased by 38% compared to that in 2005. In contrast, the NO_2 VCD present continual increases during this period, except for slight decreases

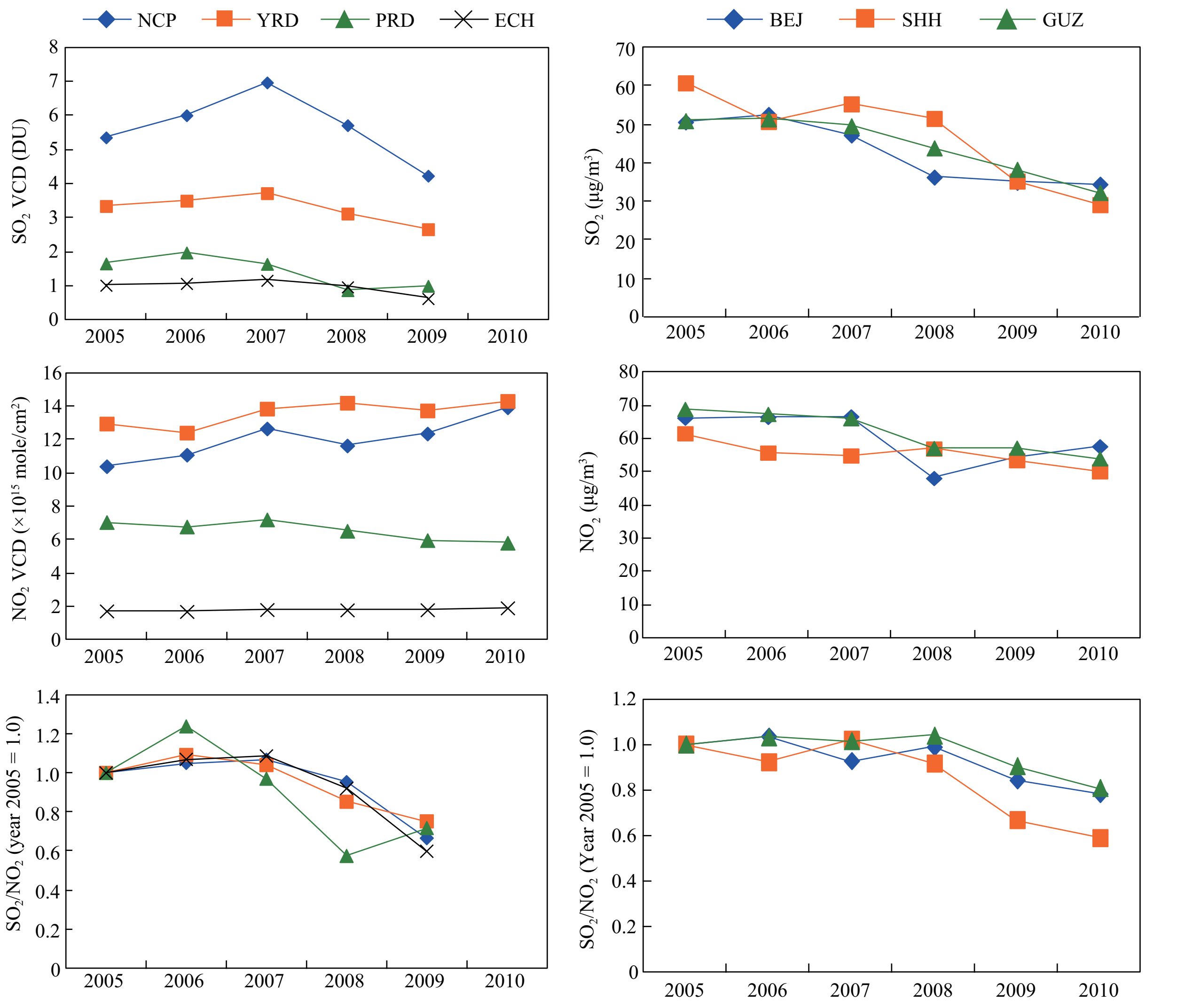


Fig. 3 Observed annual mean concentrations of SO_2, NO_2 and the SO_2/NO_2 ratio during 2005–2010. BEJ: Beijing; SHH: Shanghai; GUZ: Guangzhou; VCD: vertical density.

Table 4 Simulated 2010 baseline SO_2 and SO_4^{2-} concentrations and their changes in two hypothetical emission scenarios (unit: μg/m^3)

		NCP			YRD			PRD			ECH		
		BAS	ΔFYP	ΔBAU	BAS	ΔFYP	ΔBAU	BAS	ΔFYP	ΔBAU	BAS	ΔFYP	ΔBAU
SO_2	January	42.3	–14%	+22%	47.3	–14%	+23%	19.6	–13%	+22%	19.6	–14%	+23%
	July	13.0	–15%	+27%	15.7	–15%	+24%	6.7	–13%	+21%	5.2	–15%	+25%
SO_4^{2-}	January	4.9	–10%	+15%	7.9	–8%	+12%	7.0	–8%	+13%	5.0	–8%	+13%
	July	9.6	–12%	+17%	5.1	–10%	+14%	1.9	–8%	+12%	4.5	–10%	+15%

ΔFYP = (BAS – REF)/REF; ΔBAU = (BAU – REF)/REF.

in NCP and PRD when the 2008 Olympic Games and 2010 Asia Games were held in Beijing and Guangzhou respectively. The NO_2 VCD over east China increased by 11% during this period.

The data from ground monitoring stations in the three megacities indicate that both the SO_2 and NO_2 concentrations decreased during this period. This is mainly because strict new emission standards (e.g. the vehicle emission standard is stricter than in other area in China) and strengthened control measures were implemented in these megacities. But the reduction ratio of SO_2 is much larger than that of NO_2. Therefore, similar decreasing trends of SO_2/NO_2 ratio are also found in surface observations.

The comparison between the simulated and observed changes in the concentrations of SO_2 and NO_2 and the SO_2/NO_2 ratio are given in **Table 5**.

From satellite data, the reduction of SO_2/NO_2 ratio over east China is comparable with the BAS simulation (37%), at 40%. Although slightly lower reduction ratios were found in key regions, they are still much higher than the BAU simulation (11%), at 25%–33%. Similar results are shown in ground monitor data. The reduction of SO_2/NO_2 ratio is comparable with the one in the BAS simulation, at 41%. Relatively lower values are found in Beijing and Guangzhou, but higher than BAU, at 19%–22%.

From this analysis we can conclude that the effectiveness of the SO_2 controls during the 11th FYP is consistent with the observations, although anomalies in meteorological conditions may cause some uncertainties.

2.2 Effectiveness of NO*x* emission control during 12th FYP

2.2.1 Reduction in NO_2 and NO_3^- concentrations

The simulated NO_2 and NO_3^- concentrations in the 2010 baseline as well as their changes in three 2015 scenarios are given in **Fig. 4** and **Table 6**.

The highest NO_2 concentrations are found in metropolitan areas, i.e., NCP, YRD and PRD, where the NO_2 levels are 7.0, 9.7 and 5.4 times higher than the average of east China, respectively. They would further increase by 6%–9% if no measures are taken during 2010–2015. The 12th FYP controls will reduce the NO_2 concentrations by 8% over east China, and the three regions in particular will have NO_2 concentrations reduced by 6%–16% in 2015. The application of the new emission standard for power plants will further reduce the NO_2 concentrations by 2%–4% in the three regions.

Higher NO_3^- concentration can be also found in these metropolitan areas compared to east China. The NO_2 levels in NCP, YRD and PRD are 7.2, 6.8 and 2.3 times higher than the average of east China, respectively. Although higher NO_3^- concentration is found in January, its responses to the changes of NO*x* emissions are much smaller than that in July, especially for NCP and YRD. That is because of the nonlinear behavior under the NO*x*-rich regime in winter (Wang et al., 2011b). For example, the reduction of NO*x* emission will enhance the daytime atmospheric oxidization then increase the percentage of NO_3^- formation from NO_2, which would compensate for

Table 5 Comparison between the simulated and observed changes of the concentrations of SO_2 and NO_2 and the SO_2/NO_2 ratio during 2005–2010

Type		Region	ΔSO_2	ΔNO_2	$\Delta(SO_2/NO_2)$
Simulation	BAU	ECH	+23%	+37%	–11% (without 11th FYP)
	BAS	ECH	–14%	+37%	–37% (with 11th FYP)
Observation	Satellite	ECH	–38%	+11%	–40%
		NCP	–21%	+34%	–33%
		YRD	–20%	+10%	–25%
		PRD	–39%	–18%	–28%
	Monitor	Beijing	–32%	–13%	–22%
		Shanghai	–52%	–19%	–41%
		Guangzhou	–37%	–22%	–19%

Two months (January and July) mean for simulations, annual mean for observation, $\Delta(SO_2/NO_2) = (1 + \Delta SO_2)/(1 + \Delta NO_2) - 1$.

Table 6 Simulated NO_2, NO_3^-, O_3 concentrations and total nitrogen deposition (TN) in 2010 baseline as well as their changes in three 2015 scenarios

		NCP				YRD				PRD				ECH			
		BAS	Δ_1	Δ_2	Δ_3	BAS	Δ_1	Δ_2	Δ_3	BAS	Δ_1	Δ_2	Δ_3	BAS	Δ_1	Δ_2	Δ_3
NO_2	Jan	38.5	+8	–6	–9	44.2	+7	–13	–15	28.7	+6	–9	–11	4.6	+10	–9	–13
(μg/m^3)	Jul	12.5	+9	–8	–12	24.2	+9	–16	–19	12.5	+7	–12	–14	1.8	+6	–7	–10
NO_3^-	Jan	19.3	–1	–1	–2	22.9	0	0	–1	8.9	+3	–5	–7	3.6	+2	–3	–5
(μg/m^3)	Jul	13.6	+10	–13	–19	8.2	+8	–17	–21	1.8	+2	–8	–10	1.0	+10	–14	–20
O_3 (μg/m^3)	Jul	141.8	+1	–2	–4	123.4	+1	–3	–4	94.1	–1	+1	+1	82.0	+1	–2	–2
TN	Jan	0.9	+3	–2	–4	1.5	+4	–6	–8	1.8	+5	–7	–9	0.4	+4	–4	–6
(kg/(ha·month))	Jul	8.8	+2	–3	–4	7.0	+3	–5	–6	3.7	+2	–4	–5	1.5	+2	–2	–3

Δ_1(%) = (BAU – BAS)/BAS; Δ_2(%) = (FYP – BAS)/BAS; Δ_3(%) = (POW – BAS)/BAS.
Monthly mean of NO_2, NO_3^- and TN deposition, monthly mean of daily 1-hr maxima O_3.

the total reduction of NO_3^-. Therefore, with the continual growth of NO*x* emission in BAU, the NO_3^- concentrations would increase by only 0–3% in January, but 2%–10% in July. The 12th FYP controls on NO*x* emission will result in 0–5% reduction of NO_3^- concentration in January, but 8%–17% in July; and the application of the new emission standard for power plants will further reduce the NO_3^- concentrations by only 1%–2% in January, but by 2%–6% in July.

2.2.2 Impacts on O_3 concentrations

The simulated O_3 (daily 1-hr maxima concentration) in the July 2010 baseline as well as the changes in three 2015 scenarios are given in **Fig. 5** and **Table 6**.

As with NO_2 and NO_3^-, higher O_3 concentrations are found in these metropolitan areas. If no controls are applied, the O_3 level would increase by 1% over east China. The 12th FYP control on the NO*x* emission will benefit the reductions in regional O_3 by 2%. Application of the new emission standard for power plants will further reduce the regional O_3 by 2% in the three regions. However, local O_3 in megacities, e.g., Beijing, Shanghai and Guangzhou, will get worse under such a reduction of NO*x* emission due to its adverse effect in a NO*x*-rich regime. Synchronous control of VOCs must be taken into account in these cities (Xing et al., 2011b).

2.2.3 Reduction in total nitrogen deposition

In this study, the total nitrogen deposition (TN) is defined as wet and dry deposition of NO_3^-, HNO_3, NH_3, N_2O_5, NO, NO_2, peroxyacetyl nitrate, HONO, and organic nitrate (all counted as nitrogen). The simulated TN in the 2010

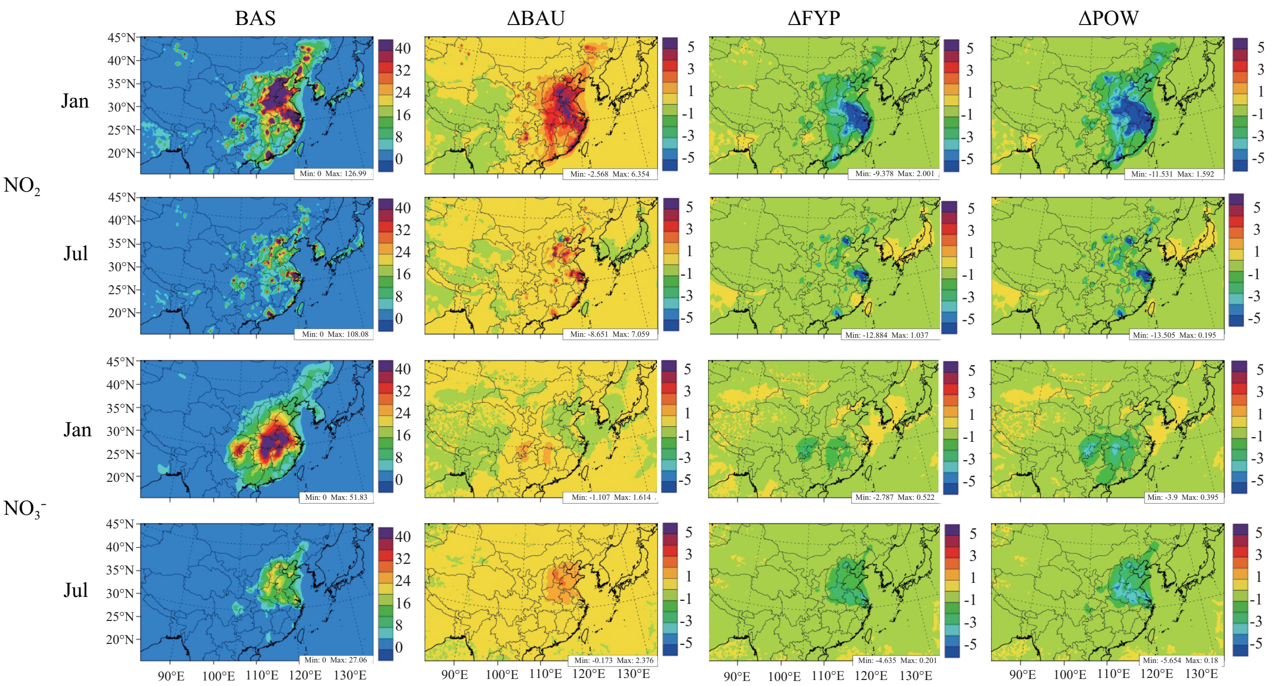


Fig. 4 Simulated NO_2 and NO_3^- concentrations in 2010 baseline as well as their changes in three 2015 scenarios (monthly mean, unit: μg/m^3). ΔBAU = BAU - BAS; ΔFYP = FYP – BAS; ΔPOW = POW – BAS.

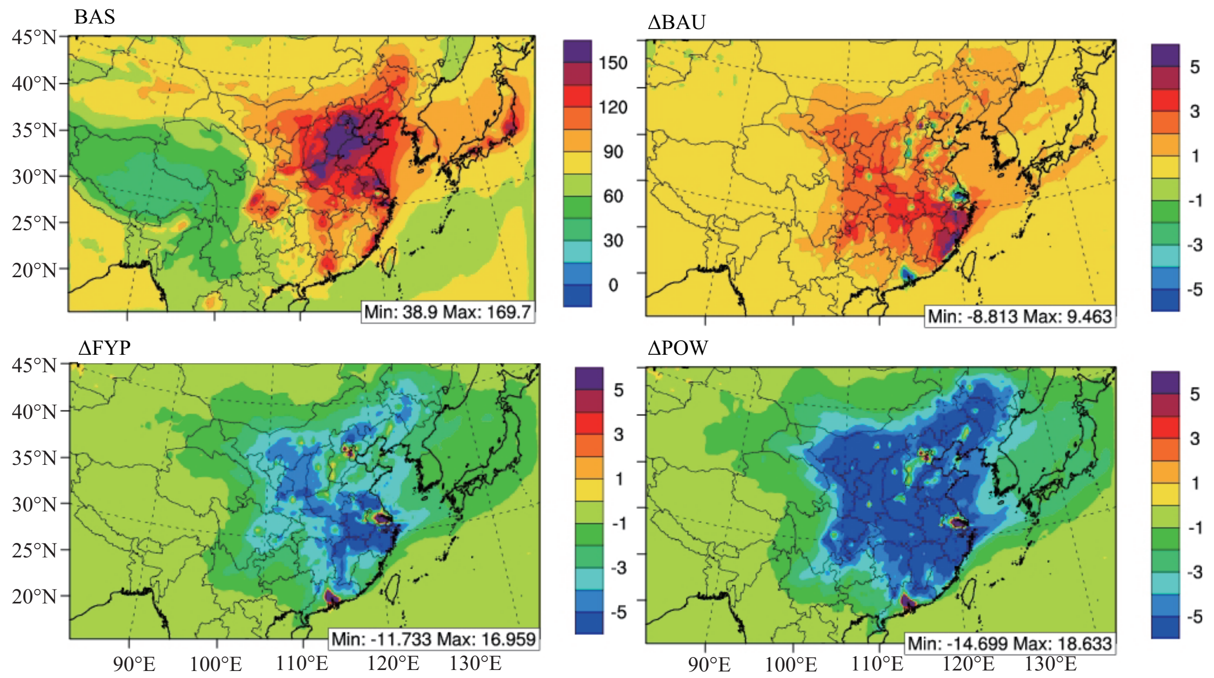


Fig. 5 Simulated O_3 concentration in July 2010 baseline as well as its changes in three 2015 scenarios (monthly mean of daily 1-hr maxima, unit: μg/m^3). ΔBAU = BAU – BAS; ΔFYP = FYP – BAS; ΔPOW = POW – BAS.

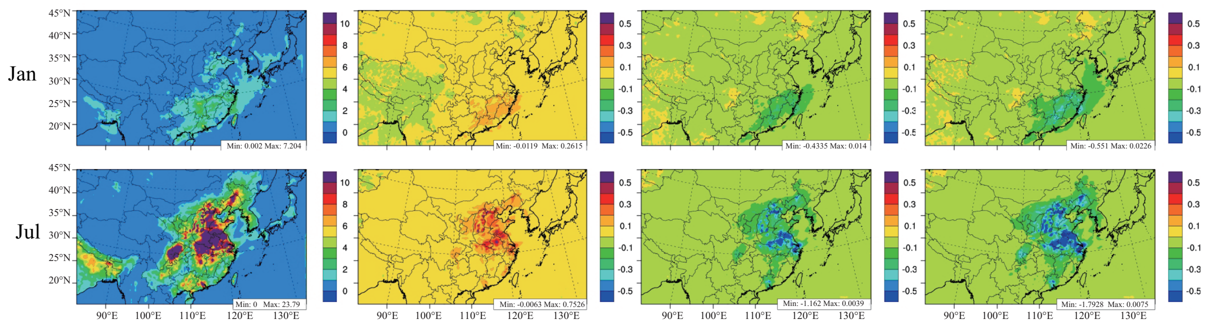


Fig. 6 Simulated total nitrogen deposition in 2010 baseline as well as its changes in three 2015 scenarios (monthly mean, unit: kg/(ha·month)). ΔBAU = BAU – BAS; ΔFYP = FYP – BAS; ΔPOW = POW – BAS.

baseline as well as its changes in three 2015 scenarios are given in **Fig. 6** and **Table 6**.

Similar to NO_2 and NO_3^-, higher TN is found in east China. The difference is that higher TN is found in July due to higher frequency of rain. If no controls are applied, the TN would increase by 2%–4% over east China. The 12th FYP control on NO*x* will benefit the reduction in TN by 2%–6%. Application of the new emission standard for power plants will further reduce the regional TN by 1%–2%.

2.3 Necessity of joint regional air pollution control

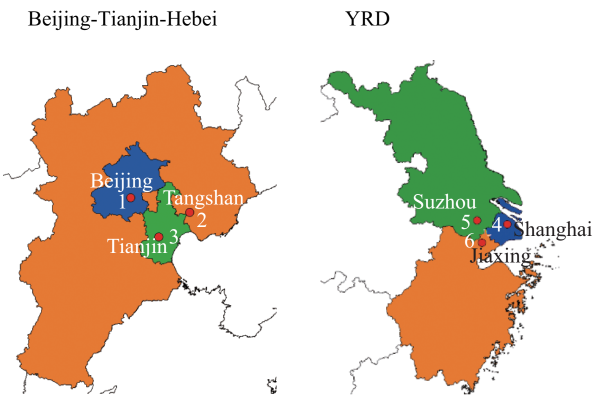
2.3.1 Sensitivity analysis design

On May 11, 2010, China issued the Guiding Opinions on Pushing Forward the Joint Prevention and Control of Air Pollution to Improve Regional Air Quality. Three regions, i.e., Beijing-Tianjin-Tangshan, YRD and PRD have been selected for beginning the implementation of regional air pollution joint prevention and control. In this article, we conducted sensitivity analysis with the CMAQ model to identify the regional contributions to the air pollution in target cities. Two key regions which involve interprovincial co-operation were selected as target areas, i.e., Beijing-Tianjin-Tangshan and YRD. We also chose one city in each province as the target cities, as seen in **Fig. 7**.

The sensitivity analysis was conducted by reducing 10% of total SO_2 and NO*x* emissions from each individual province in turn. The air quality changes in the controlled simulation from the baseline are regarded as the control effectiveness by individual emission reductions in each province.

Table 7 Comparison of local and regional control effectiveness in target cites (response to 10% controls on SO_2/NO*x* emissions from individual province (unit: %)

Beijing-Tianjin-Hebei		Beijing urban center				Tianjin urban center				Tangshan urban center			
		SO_2	NO_2	SO_4^{2-}	NO_3^-	SO_2	NO_2	SO_4^{2-}	NO_3^-	SO_2	NO_2	SO_4^{2-}	NO_3^-
Jan	Beijing	7.7	3.8	2.8	–0.4	0.2	0.2	0.2	–0.3	0.2	0.4	0.2	0.1
	Tianjin	0.2	0.1	0.1	–0.3	8.7	3.8	5.6	0.2	1.6	1.4	1.0	–0.6
	Hebei	1.8	0.3	1.4	–0.1	0.8	0.2	0.9	0.3	7.7	4.1	4.5	–0.5
Jul	Beijing	5.4	7.3	0.8	0.6	0.1	0.0	0.1	0.4	0.1	0.0	0.2	0.4
	Tianjin	1.8	0.4	0.8	2.1	8.9	7.0	1.9	1.4	1.5	1.4	0.6	1.2
	Hebei	2.6	0.4	2.3	3.7	0.7	0.2	1.4	3.0	7.8	8.6	2.8	3.1
YRD		**Shanghai urban center**				**Suzhou urban center**				**Jiaxing urban center**			
		SO_2	NO_2	SO_4^{2-}	NO_3^-	SO_2	NO_2	SO_4^{2-}	NO_3^-	SO_2	NO_2	SO_4^{2-}	NO_3^-
Jan	Shanghai	8.1	3.7	3.8	–0.2	0.5	0.3	0.3	–0.2	0.8	0.7	0.7	–0.1
	Jiangsu	1.2	0.1	0.5	0.5	2.9	1.7	1.4	–1.1	0.6	0.3	0.4	0.3
	Zhejiang	0.1	0.0	0.0	0.2	6.1	2.8	1.7	–0.2	8.4	3.9	2.8	–0.1
Jul	Shanghai	9.3	5.7	2.8	0.3	0.8	0.5	0.3	0.6	0.0	0.0	0.1	0.2
	Jiangsu	0.2	0.1	0.4	1.3	8.6	6.1	2.7	0.4	0.1	0.2	0.1	0.3
	Zhejiang	1.1	0.7	1.1	4.3	1.2	0.8	1.6	6.1	10.1	9.1	4.5	8.3



1. Beijing urban (Beijing)
2. Tianjin urban (Tianjin)
3. Tangshan urban (Hebei)
4. Shanghai urban (Shanghai)
5. Suzhou urban (Jiangsu)
6. Jiaxing urban (Zhejiang)

Fig. 7 Target areas and cities in multi-regional sensitivity analysis.

2.3.2 Inter-provincial impacts of emission reduction

Table 7 gives the control effectiveness of 10% reduction of SO_2 and NO*x* emissions applied to individual provinces. It is clearly seen that such a reduction in a certain province may not only benefit the improvement of local air quality inside the province, but also has a considerable contribution to improve the air quality in nearby cities, particularly for secondary species like SO_4^{2-} and NO_3^-.

For the Beijing-Tianjin-Hebei region, the control of 10% emissions in Tianjin will reduce 9% SO_2, 4% NO_2 and 6% SO_4^{2-} there, and also reduce 2% of SO_2, 1% of SO_4^{2-}, 1%–2% of summer NO_2 and NO_3^- in Beijing and Tangshan. The 10% emission control in Hebei not only improves the local air quality in Tangshan, but also greatly benefits the reduction of SO_2 (1%–2%), SO_4^{2-} (1%–2%) and summer NO_3^- (2%–4%) in Beijing and Tianjin. Although the impacts from 10% emission reduction in Beijing on the other two cities are relatively small, there is still 0.4% reduction of summer NO_3^- (0.4%) for Tianjin and Tangshan.

Similar results are also found in YRD. The 10% emission control in Zhejiang will not only reduce the air pollution in Jiaxing, but also reduce 1–2% of SO_2 and SO_4^{2-}, 1% of NO_2 and 4%–6% of NO_3^- in Shanghai and Suzhou in summer, even more effective than local emission control in Suzhou in winter. The 10% emission control in Jiangsu will also reduce 1%–2% of SO_2, 0.8% of SO_4^{2-}, and 0.1%–2% of NO_3^- in Shanghai and Jiaxing. Emission control in Shanghai will reduce 1% of SO_2, NO_2 and SO_4^{2-} in Jiaxing during winter, as well as 0.5%–1% of SO_2, NO_2 and NO_3^- and SO_4^{2-} in Suzhou in summer.

3 Conclusions

Based on the modeling sensitivity analysis, the effectiveness of the 11th and 12th FYP national control policies in improvement of air quality in China was evaluated. The controls of SO_2 and NO*x* emissions during the 11th and 12th FYPs have improved the air quality in metropolitan areas of China, particularly the ambient SO_2, NO_2 and inorganic aerosol concentrations. The SO_2 and NO*x* emission reductions benefited regional O_3 and total nitrogen deposition, but more efforts are still needed to further control the NO*x* emissions as well as the emissions of VOC and NH_3.

There are significant inter-provincial impacts among the cities within the Hebei-Beijing-Tianjin area and YRD, so the actions of regional joint controls can improve the regional air quality more efficiently. Since the effects of multi-region control can be different from the sum of individual effects, this study has limitations in solving the nonlinear issue. But considering the nonlinear issue for O_3 and NH_3, the effectiveness of emission reduction will be strengthened with stricter control efforts. Therefore, the effects of regional joint controls shall be more significant.

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