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Projections of air pollutant emissions and its impacts on regional air quality in China in 2020

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Abstract

Anthropogenic emissions of air pollutants in China influence not only local and regional environments but also the global atmospheric environment; therefore, it is important to understand how China's air pollutant emissions will change and how they will affect regional air quality in the future. Emission scenarios in 2020 were projected using forecasts of energy consumption and emission control strategies based on emissions in 2005, and on recent development plans for key industries in China. We developed four emission scenarios: REF[0] (current control legislations and implementation status), PC[0] (improvement of energy efficiencies and current environmental legislation), PC[1] (improvement of energy efficiencies and better implementation of environmental legislation), and PC[2] (improvement of energy efficiencies and strict environmental legislation). Under the REF[0] scenario, the emission of SO_2, NO_x, VOC and NH_3 will increase by 17%, 50%, 49% and 18% in 2020, while PM will be reduced by 10% over East China, compared to that in 2005. In PC[2], sustainable energy polices will reduce SO_2, NO_x and PM_{10} emissions by 4.1 Tg, 2.6 Tg and 1.8 Tg, respectively; better implementation of current control policies will reduce SO_2, NO_x and PM_{10} emission by 2.9 Tg, 1.8 Tg, and 1.4 Tg, respectively; strict emission standards will reduce SO_2, NO_x and PM_{10} emissions by 3.2 Tg, 3.9 Tg, and 1.7 Tg, respectively. Under the PC[2] scenario, SO_2 and PM_{10} emissions will decrease by 18% and 38%, while NO_x and VOC emissions will increase by 3% and 8%, compared to that in 2005. Future air quality in China was simulated using the Community Multi-scale Air Quality Model (CMAQ) with 2005 emissions and 2020 emission scenarios. Under REF[0] emissions, the concentrations of SO_2, NO_2, hourly maximum ozone in summer, $PM_{2.5}$, total sulfur and nitrogen depositions will increase by 5∼47%, 45∼53%, 8∼12%, 4∼15%, 4∼37% and 7∼14%, respectively, over East China. Under the PC[2] emission scenario, the concentrations of SO_2, NO_2, hourly maximal ozone in summer, $PM_{2.5}$, total sulfur and nitrogen depositions will change by −28%∼16%, −1%∼11%, 1%∼2%, −24%∼−12%, −24%∼13%, and 0∼3%, respectively. The individual impacts of SO_2, NO_x, NH_3, NMVOC and primary PM emission changes on ozone and $PM_{2.5}$ concentrations have been analyzed using sensitivity analysis. The results suggest that NO_x emission control need to be enhanced during the summertime to obtain both ozone and $PM_{2.5}$ reduction benefits. NH_3 emission controls should also be considered in order to reduce total nitrogen deposition in the future.

1 Introduction

With the fast growth of the domestic economy and urbanization in China, the emissions of air pollutants from coal combustion, industrial production, and transport have been increasing at an unprecedented rate over the last decade. From 1995 to 2005, the annual growth rates of energy consumption, cement production, steel production, and the vehicle population, were 10%, 24%, 12%, and 10%, respectively. The observations from satellite remote sensing indicate that NO_x emissions in the Central and East China have accelerated by a factor of 2 during 2000~2006 (Richter et al., 2005). There is evidence that anthropogenic emissions of air pollutants in China are influencing not only local and regional, but also the global atmospheric environment (Wild and Akimoto, 2001; Liang et al., 2004; Dickerson et al., 2007). A better understanding of the emissions of air pollutants and their impact on air quality is therefore of great interest.

In 2009, the total energy consumption in China reached 3.1 billion tons of coal equivalents (tce), of which 69% is from coal (NBSC, 2010). China has overtaken the United States to become the world's largest energy user. What is more important is that the growth of energy consumption will continue into future because the energy consumption on a per capita basis is still only about one-third of the OECD average. Therefore, there are strong indications that emissions of air pollutants will keep increasing in the next decade. Future changes in air quality will be affected strongly by the expected changes in anthropogenic emissions, which are controlled by economic growth, environmental policy, and the future implementation of emissions controls. In light of this situation, the projections of future emissions are essential to designing cost-effective

mitigation strategies and to understanding how the emissions affect the future air quality in China and Asia (Dentener et al. 2006; Unger et al., 2006).

Projections of Chinese (as part of Asia) emissions from fuel combustion and industrial sources have been made by Van Aardenne et al. (1999) for NO_x, Streets and Waldhoff (2000) for SO_2, NO_x, and CO, Klimont et al. (2001) for SO_2, NO_x, NH_3, and NMVOC, and Ohara et al. (2008) for SO_2, NO_x, CO, NMVOC, black carbon (BC), and organic carbon (OC). Some studies have also forecast surface ozone levels over East Asia for the year 2020, indicating that NO_x (NO_x=NO+NO_2) and ozone would be a potential issue (Yamaji et al., 2008). These early projections suffered from poor data availability and were too optimistic about the pace of the introduction and effectiveness of environmental legislation. These projections also underestimated the economic growth experienced in the last decade in China (Klimont et al., 2009).

Based on the most recent development plan for key industries and on new information on local emission factors in China, this paper presents possible emission scenarios for SO_2, NO_x, non-methane volatile organic compounds (NMVOCs), NH_3 and primary particles (PM), and the potential impacts of emission changes on the regional air quality in China for the year 2020. Twenty-five simulations, a 2005 base case and twenty-four hypothetical 2020 emission scenarios, have been run and analyzed using the Community Multi-scale Air Quality Model (CMAQ) for four months (January, April, July, and October). The next section describes the methodology used for the energy consumption forecast, the air pollution control legislation considered and the corresponding future emission scenarios. Section 3 presents the model output concentrations of SO_2, NO_2, fine particles, ozone, sulfur and nitrogen deposition based on emissions in 2005 (the base year) and in 2020. Conclusions and recommendations for future air pollution control policies are provided in Sect. 4.

2 Projection of SO_2, NO_x, PM, NMVOC and NH_3 emissions in China

The regions studied covered 31 provinces, autonomous regions and municipalities over mainland China. Hong Kong, Macao and Taiwan were not included. SO_2, NO_x, and PM with different size fractions (TSP, PM_{10}, and $PM_{2.5}$), NMVOC and NH_3 were the targeted pollutant species. All data were at the provincial level. For a given Province i, year y, and pollutant n considered in this paper, the emissions were calculated using the following equations:

$$E_{n,y} = \sum_{i,k,l} A_{i,k,l,y} \sum_{m} \left[\mathrm{ef}_{i,k,l,n}(1-\eta_{i,k,m,n})X_{i,k,l,m,y}\right] \ (0 < X \le 1) \quad (1)$$

$$E_{n,y} = \sum_{i,k,l} A_{i,k,l,y}\mathrm{ef}_{i,k,l,n} \ (X = 0) \quad (2)$$

where, i represents the Province (administrative region); k represents the economic sector or combustion technology type; l represents the fuel type (if relevant for a specific k); m represents the abatement technology type; E is the national annual emissions; A is the activity level (e.g. fuel consumption, industrial production, amount of biomass burned on-field); ef is the uncontrolled emission factor; η is the reduction efficiency of the abatement technology; and X is the penetration of the abatement measure m expressed as a percentage of total activity A.

2.1 Projection of energy consumption

The energy consumption level was estimated in collaboration between the research groups at International Institute for Applied Systems Analysis (IIASA) in Laxenburg (Austria), Tsinghua University and Energy Research Institute (ERI) in Beijing (China) (Amann et al., 2008). The new projection reflects current Chinese expectations with regard to (i) population projections from the National Population Development Strategy, (ii) the official Chinese industrial process forecasts, (iii) the 1997–2010 Land Plan

Program from the Ministry of Land and Resource (2004), and (iv) the national development targets for renewable energy sources in the “11th Five-Year Plan”. The projection framework for the energy scenarios is shown in Fig. 1. The most important driving forces for energy consumption were population, GDP and wealth. We predict that the population will be 1.44 billion and the GDP will be 48.2 trillion RMB by 2020. Fuel consumption and industrial production were forecast using a logistic model. The dependent variables, such as future electricity generation, industrial energy consumption and industry production, were calculated using regression analysis based on historical data and the GDP (independent variables). The improvement of energy efficiency and technological progress were also used in our calculation.

We developed two energy scenarios, a reference scenario or baseline (REF) which was based on current development trends, and an energy policy scenario (PC) which assumed that more sustainable energy development strategies will be adopted in the future. Scenario assumptions and key macroeconomic parameters are given in Table 1.

In 2020, total energy consumption is projected to be 134 165 PJ under the REF scenario and 122 493 PJ under the PC scenario, respectively. Compared to 2005, the energy consumption of power plants, industry and transportation in 2020 would increase sharply, as shown in Fig. 2a. From 2005 to 2020, energy use by power plants will increase by 117% under the REF scenario and 92% under the PC scenario, respectively. Jiangsu, Guangdong and Shandong are top power generation Provinces. From 2005 to 2020, energy consumption by industry will increase 82% under the REF scenario and 68% under the PC scenario, respectively. Shandong, Hebei and Shanxi are the top three industrial Provinces. Energy consumption by on-road transport in 2020 will increase 203% under the REF scenario and 190% under the PC scenario compared to that in 2005. Guangdong, Shandong and Beijing consume up to 30% of the total transport energy consumption in 2020. The sectoral fuel use by each Province and each scenario is given in Table 2.

The change of the fuel structure in each sector has also been considered in this study, as shown in Fig. 2b. Although coal will still be the most important fuel for power plants and industries, the percentage of oil and gas will grow at a much faster rate. Under the REF and PC scenarios, the annual growth rate of oil is 1.28 and 1.81 times that of coal used in power plants and 1.88 and 1.76 times that of coal used in industry, respectively. The percentages of the total energy consumption for coal, oil, gas and bio-fuel are 66%, 13%, 10% and 10% in 2005, 68%, 16%, 10% and 7% in the REF scenario, and 65%, 17%, 11% and 7% in the PC scenario.

2.2 Uncontrolled emission factors

Uncontrolled emission factors were obtained from recent references, which reported measurements from Chinese sources. The literature was thoroughly searched for published data for emission factors from domestic field measurements at power plants (Tian, 2003; Zhu et al., 2004; Yi et al., 2006; Zhao et al., 2008, 2010), industrial boilers (Wang et al., 2008; Li et al., 2007; Lei et al., 2008), and biomass and bio-fuel burning (Li et al., 2007, 2009). A survey of the open burning of crop residues was conducted (Wang et al., 2008). Data on NMVOC emission characteristics measured in China were also collected, which included stoves burning bio-fuel and coal, road transportation, certain industrial and domestic sectors using solvent, fugitive emissions from oil exploration and distribution, and open burning of biomass (Wei et al., 2008; Wang et al., 2009). A dataset of emission factors has been documented based on these papers. All emission factors, and other assumptions used in this study can be viewed at the on-line version of the GAINS-Asia model (http://gains.iiasa.ac.at/), while a more detailed description is also available in the methodology document (Amann et al., 2008).

2.3 Air pollution control legislation

Three potential air pollution control scenarios were designed for 2020, including a baseline scenario, a better implementation scenario, and a strict policy scenario. The baseline scenario (strategy-[0]) assumed that all current legislation and the implementation status of proposed legislation would be followed during 2005~2020. The better

implementation scenario (strategy-[1]) considered the enhanced enforcement of current legislation and planned air pollution control measures. The strict policy scenario (strategy-[2]) assumed strict control policies and that more advanced control technologies would be implemented during 2005~2020. Tables 3~5 summarizes the progress of alternative technologies on air pollution control measures under the various scenarios.

2.3.1 Sulfur dioxides (SO_2)

Table 3 gives the penetration of SO_2 control measures assumed under the three control scenarios. In strategy-[0], the most important SO_2 control measure is the installation of flue gas desulfurization (FGD) in power plants. The Chinese government wants to reduce national SO_2 emissions by 10% in 2010 on the basis of that in 2005. To achieve this goal, FGD devices are now being widely installed in coal-fired power plants. In 2005, only 15% of the power plants had FGD. By 2009, the percentage has increased to 71%. Considering that all newly-built power plants will install FGD, and some of the older plants will be retired, the percentage will continue to increase during 2010–2020. We project that in 2020, the power plants with FGD will account for 81%, 95% and 95% under strategy-[0], strategy-[1] and strategy-[2], respectively. Currently, there is no effective measure in place to control SO_2 emissions from industrial boilers. In strategy-[1], enforcement of legislation will be strengthened so that industries can meet the current emission standards, and 50% of the coal used in industries will be low sulfur coal or briquette. In strategy-[2], 30% of the industrial boilers will install FGD in order to meet emission standard. In all three strategies, Limestone Injection into Furnace (LIN) technology will be applied to all Circulating Fluidized-Bed (CFB) Boiler. In the domestic sector, there are no control efforts being considered under baseline strategy-[0]. Under strategy-[1], we assume the application of low sulfur coal or briquette in domestic stoves will increase up to 80% in 2020. Under strategy-[2], we assume that new emission standards will be implemented for small domestic boilers; therefore, 80% of domestic boilers will use low sulfur coal or briquette in 2020.

Industry processes including cement plants, lime plants, coking plants and sinter plants are important SO_2 sources as well. For cement plants, the units with out-of-date technology such as rotary kilns and vertical kiln will be shut down. As shown in Table 4, by 2020, the percentage of advanced precalcining kilns will increase to 91% in the cement industry, which decreases the SO_2 emission factor (EF) by 53% compared to that in 2005. The lime plants using early kilns will decrease from 70% in 2005 to 13% in 2020, while those using modern kilns will increase from 30% in 2005 to 87% in 2020. All the indigenous coke plants will also be closed before 2020. For sinter plants, desulfurization technology is not practical under strategy-[0] and strategy-[1]. In strategy-[2] we assume that from 2015, more effort will be made to improve the control technology used in sinter plants, and that EF will be decreased by 30% in 2020 compared to that in 2005.

2.3.2 Nitrogen oxides (NO_x)

Current NO_x emission control in China only involves power plants and on-road vehicles. By 2005, only about 46% of power plants had installed low NO_x burners (LNB). Considering that all newly-built power plants will use LNB, the application of LNB will increase to 85% in strategy-[0] by 2020. On 27 January 2010, the Ministry of Environmental Protection of the People's Republic of China (MEP) issued their "Notice of Fossil-Fired Power Plant NO_x Emission Prevention and Treatment Policy" (the "Notice"). This "Notice" sets the framework for NO_x reduction actions to be taken under the nation's 12th Five-Year Plan, which begins 1 January 2011. In general, the policy set forth in the "Notice" applies to all coal-fired power plants and co-generation units that are 200 MW or larger, except those in designated "Focus Areas" (areas around Beijing, Shanghai, and Guangdong) where it applies to all units regardless of size. For the units covered by the "Notice", all new, or rebuilt units that have undergone expansion should install low-NO_x combustion technologies (such as LNB and Over-Fire Air systems) as a first step. For operating units, if the NO_x emission levels cannot meet the emission standard, then the unit should install flue gas de-NO_x technology. Major flue gas de-NO_x technolo-

gies mentioned in the "Notice" includes Selective Catalytic Reduction (SCR), Selective Non-Catalytic Reduction (SNCR), and SNCR-SCR systems. Considering the implementation of this "Notice", we assume that in strategy-[1], Chinese government will promote SCR and SNCR installation in new or rebuilt power plants during 2010~2020. In 2020, the application of SCR will reach 30% under strategy-[1]. In strategy-[2], we assume stricter emission standards will be released and all new units will install SCR; therefore, the application ratio of SCR will increase to 55% in 2020.

Due to the lack of available control technologies, there are no controls on industrial boilers in both strategy-[0] and strategy-[1]. In strategy-[2], we assume that all newly-built industrial boilers will install LNB. The application ratio of LNB will increase to 32% in 2020.

For the transportation sector, both strategy-[0] and strategy-[1] will follow current mobile sources control policy, while strategy-[2] assumes that starting from 2012, Euro-V will be applied to light-duty cars, Euro-III will be applied to agriculture and construction machines, and Euro-I and Euro-II will be applied to inland water ships.

Cement plants are also an important source of NO_x. Strategy-[0] and strategy-[1] do not consider NO_x emission control in cement production. Strategy-[2] assumes that SNCR will be applied to those cement plants with the precalcining technique after 2015.

2.3.3 Particulate matter (PM)

In China, the control of particulate matter has achieved noticeable progress. A new, strengthened PM emission standard for power plants was published in 2003 (SEPA, 2003). Since then, all new and rebuilt units have to meet the PM emission standard with PM concentrations in flue gas less than $50\,\mathrm{mg\,m^{-3}}$. As a result, over 92% of pulverized coal units installed electrostatic precipitators (ESP). In addition, fabric filters have been put into commercial use for the units with a capacity of over 600 MW. In future scenarios, the ratio of units with fabric filters will increase to 15%, as shown in Table 3. In addition, all grate boilers using wet scrubbers or cyclones will be phased out or shut down. The percentage of grate boilers will decrease from 3.9% in 2005 to 1.7% in 2020.

Currently, industrial boilers either installed wet scrubbers or cyclones to remove PM in the flue gas. In strategy-[0], we assume that new industrial and domestic boilers will be equipped with wet scrubber. Strategy-[1] assumes both new and old boilers will be renovated with wet scrubber. Strategy-[2] suggests stricter emission standards, and new industrial and domestic boilers will be equipped with fabric filters and wet scrubbers, respectively.

2.3.4 Non-methane volatile organic compounds (NMVOC)

Up to 2009, the existing national legislation to limit NMVOC emissions covered road vehicles (China standards GB/14622, GB/14762, GB/17691, GB/18352, GB/19756), non-road diesel engines (China standard GB/20891), wood paints (China standard GB/18581), indoor decorative paints (China standard GB/18582), adhesives used in shoemaking (China standard GB/19340), and petroleum oil distributions (China standards GB/20950~GB/20952). In this study, strategy-[0] and strategy-[1] follow these current NMVOC control legislation. Strategy-[2] assumes further controls on VOC emissions from solvent use, the chemical industry, and oil refinery plants, as shown in Table 5. The application rate of end-of-pipe treatments for related industries is 40% in 2020, which is at a level similar to EGTEI (2008). The removal efficiencies of various measures are given in Table 5 (European Commission, 2001; EGTEI, 2008). Detailed assumptions made during the control policy design period are discussed in Wei (2009). With the implementation of these measures, NMVOC emissions under strategy-[2] are 10~85% less compared to that under strategy-[0] and strategy-[1].

2.3.5 Ammonia (NH_3)

Although NH_3 is one important precursor of inorganic fine particles, NH_3 emission control has not received much attention in the current air pollutant control strategy in China.

Our previous studies indicated that NH_3 emissions have been increasing at an annual growth rate of 3.1% from 1994 to 2006 (Dong et al., 2010). The potential increase of NH_3 emission in the future will enhance the fine particle pollution. In strategy-[0], we project the future NH_3 emissions using a logistic method and historical emission data without considering any control in 2020. In strategy-[2], we assume the NH_3 emissions will be at same level as that in 2005.

2.4 Future emissions estimations

In this study, we calculated four emission scenarios based on the above energy scenarios and emission control strategies. These emission scenarios are REF[0] (with the REF energy scenario and Strategy-[0]), PC[0] (with the PC energy scenario and Strategy-[0]), PC[1] (with the PC energy scenario and Strategy-[1]), and PC[2] (with the PC energy scenario and Strategy-[2]).

The predicted national SO_2, NO_x, and PM_{10} emissions for different scenarios are given in Fig. 3. Changes in SO_2, NO_x, PM_{10}, NMVOC and NH_3 emissions by each province for different scenarios are shown in Fig. 4. The changes for regional emissions for 2020 scenarios are given in Table 6.

2.4.1 Future SO_2 emissions

The SO_2 emissions were 28.6 Tg in 2005. In 2020, SO_2 emissions will grow to 33.0 Tg under the REF[0] scenario or decrease to 22.9 Tg under the PC[2] scenario. SO_2 emissions decrease during the period 2005 to 2010, mainly due to FGD installations in power plants. The REF[0] scenario indicates a rapid increase of SO_2 emissions from industrial boilers after 2010. Industrial boilers will replace power plants to become the largest SO_2 emission sources. Under the PC[2] scenario, SO_2 emissions from industrial boilers are mainly reduced by the installation of FGD after 2015.

Different control measures have different emission reduction potentials. In PC[2], energy savings and the improvement of energy efficiency will reduce SO_2 emissions by 4.1 Tg. Application of low sulfur coal or briquettes in the industrial and domestic sectors will reduce SO_2 emissions by 2.9 Tg. Installation of FGD in industrial boilers may reduce SO_2 emissions by 3.2 Tg.

High SO_2 emission levels are found in East China (ECH) including the North China Plain (NCP), the Yangtze River Delta (YRD), the Pearl River Delta (PRD), as well as in the Si-chuan basin. Comparing emission levels in 2020 with those in 2005, the SO_2 emissions in NCP, YRD, PRD and ECH will increase by 5%, 36%, 48% and 17%, respectively in REF[0]. In PC[2], the SO_2 emissions in NCP, YRD and ECH in 2020 are −27%, −9%, and −18% lower than those in 2005. However, SO_2 emissions in PRD will grow by 17% even in PC[2] because of the significant increase in future activities in the PRD area (NDRC, 2008).

2.4.2 Future NO_x emissions

Compared to those in 2005, the national NO_x emissions in 2020 will increase 47% to 26.7 Tg in REF[0]. Even in the strict policy scenario PC[2], the NO_x emissions in 2020 will be 18.5 Tg, 2% higher than those in 2005. Power plants, industry and transportation are the most important sources of NO_x emissions, which contributed to 38%, 26%, 23%, respectively, to NO_x levels in 2005. In REF[0], NO_x emissions from power plants, industrial boilers and industrial process will increase by 73%, 92%, and 34%, respectively, compared to those in 2005.

Of all the NO_x control measures in PC[2], energy savings and the improvement of energy efficiency may reduce NO_x emissions by 2.6 Tg; application of flue gas de-nitration technology in power plants reduce NO_x emissions by 1.8 Tg; Implementation of stricter emission standards for industrial boilers will result in an increase in the installation of LNB and may reduce NO_x emissions by 3.9 Tg.

NO_x emissions levels are highest in the east coastal regions, such as NCP, YRD and PRD. In REF[0], the NO_x emissions in NCP, YRD, PRD and ECH are, respectively, 45%, 53%, 62% and 50% higher than those in 2005. After effective control measures are applied in PC[2], NO_x emissions in these regions will remain at 2005 emission levels, with change ratios of 0%, −1%, 14% and 3%, respectively.

2.4.3 Future PM_{10} emissions

In 2005, the PM_{10} emissions in China were 17.1 Tg. Future PM_{10} emissions will decrease to 16.0 Tg in REF[0] and 11.1 Tg in PC[2]. Industrial processes and the domestic sectors are the two major sources of PM_{10} emissions; they contributed 40% and 30%, respectively, to the total emissions in 2005. Compared to those in 2005, PM_{10} emissions from industrial processes, transportation, and domestic sources in REF[0] will decrease by 51%, 35%, and 11%, respectively, while power plants and industrial boilers will increase by 46% and 80%. In PC[2], installation of high efficiency dust collectors in industry will reduce PM_{10} emissions by 0.01 Tg and 5.0 Tg from industrial boilers and industrial processes, respectively, compared to those in 2005. The reduction of PM_{10} emissions by the installation of high efficiency dust collectors in industrial boilers are almost totally offset by the growth of coal combustion of this sector.

Of all the PM control measures in PC[2], energy saving and the improvement of energy efficiency may reduce PM_{10} emissions by 1.8 Tg; better implementation of emission standards may decrease the PM_{10} emissions by 1.4 Tg; Application of high efficiency dust collectors in industry may reduce PM_{10} emissions by 1.7 Tg.

As shown in Table 6, the PM_{10} emissions of NCP, YRD, PRD and ECH are, respectively, −12%, 2%, −16% and −10% in REF[0], and −42%, −29%, −34% and −38% in PC[2].

2.4.4 Future NMVOC emissions

The NMVOC emissions were 19.4 Tg in 2005. Future NMVOC emissions in China are predicted to be 26.5 Tg in REF[0] and 19.9 Tg in PC[2]. The control efforts applied in PC[2] will contribute to a 25% reductions of NMVOC emissions. Compared to those in 2005, the NMVOC emissions in NCP, YRD, PRD and ECH, respectively, increase by 50%, 87%, 47% and 49% in REF[0], and by 5%, 34%, 4% and 8% in PC[2].

2.4.5 Future NH_3 emissions

NH_3 emissions in China were 16.6 Tg in 2005. Future NH_3 emissions in China are predicted to be 19.3 Tg in 2020, 16% higher than those in 2005. Livestock and fertilizer applications are two major contributors, which account for over 90% of total NH_3 emissions. Predicted of NH_3 emissions indicate an increase in east coastal regions such as NCP, YRD and PRD in 2020. The growth rates of NH_3 emissions in NCP, YRD, PRD and ECH are 19%, 22%, 26% and 18%, respectively, in REF[0], PC[0], and PC[1]. Under PC[2], NH_3 emissions will remain the same in 2020 as those in 2005.

3 Impacts of emission changes on future air quality

3.1 Air quality modeling system

The CMAQ model, which was developed by US EPA (Byun and Ching, 1999), has been extensively evaluated by several modeling studies in Asia (Zhang et al., 2006; Streets et al., 2007; Uno et al., 2007; Fu et al., 2008; Li et al., 2008). CMAQ version 4.7 is applied in this study to simulate the air quality in China for the 2005 baseline and for the 2020 scenarios. The modeling domain covers most of China with a 36×36 km grid resolution and with nested simulations at 12-km over Eastern China, as shown in Fig. 5. A Lambert projection with the two true latitudes of 25° N and 40° N is used. The domain origin is 34° N, 110° E. The coordinates of the bottom left corner are ($x=-2934$ km, $y=-1728$ km). The vertical resolution of CMAQ includes fourteen layers from the surface to the tropopause with denser layers at lower altitudes to resolve the planetary boundary layer (PBL). The Carbon Bond Mechanism (CB05) with aqueous and aerosol extensions and the AREO5 aerosol mechanism are chosen for the gas-phase chemistry and aerosol modules, respectively. A spin-up period of seven days is used for model simulations to reduce the influence of initial conditions on model results. The boundary conditions are based on nesting from the global chemical transport model GEOS-Chem (http://acmg.seas.harvard.edu/geos/).

The fifth-generation National Center for Atmospheric Research (NCAR)/Pennsylvania State University (PSU) Mesoscale Model (MM5), version 3.7, is applied to generate the meteorological fields needed for CMAQ simulations. In the MM5 simulations, 23 sigma levels are selected for the vertical grid structure with the model's top pressure of 100 mb at approximately 15 km. The height of the first 12 levels extends up to 2 km from the surface with the lowest level at approximately 40 m. The MM5 data sources and major physics options are the same as described in our previous paper (Wang et al., 2010b). The Meteorology-Chemistry Interface Processor (MCIP) version 3.4 is applied to process the meteorological data in a format required by CMAQ.

Air quality impacts from emission changes for all species are calculated using the above MM5/CMAQ modeling system for three regions as East China (ECH, domain 2) including NCP, YRD and PRD, as shown in Fig. 5. Twenty-five emission scenarios are simulated. Except for the 2005 emissions and four future scenarios with synchronic controls on all five pollutants (REF[0], PC[0], PC[1] and PC[2]), twenty hypothetical scenarios under which only the emissions of one pollutant change and emissions of other pollutants are kept at 2005 levels have been simulated to explore the control benefit of each pollutant. The differences in the simulated air quality results between the 2005 emission scenario and those twenty-four hypothetical scenarios are defined as air quality responses.

3.2 Concentrations of SO_2 and NO_2

Concentrations of SO_2 and NO_2 are mostly affected by their primary emissions. Concentration responses of SO_2 and NO_2 to the changes of SO_2 and NO_x emissions show a near-linear relationship, which indicates that control of the relative primary emissions is an effective way to reduce these two pollutants, as shown in Fig. 6. NO_2 concentrations show a slightly non-linear relationship with NO_2 emission changes. The ratio of emission changes to NO_2 concentration responses are 0.9~1 in NCP, and 1~1.5 in YRD and PRD. The differences are mainly due to the different diffusion processes and photochemical reactions in these regions. The impact of the growth of VOC emissions are about −2%. Effects due to the increase in VOCs will enhance daytime photochemical reactions and provide more OH to react with NO_2 to generate HNO_3.

Following the continual increase of SO_2 and NO_x emissions in REF[0], SO_2 and NO_2 concentrations will increase by 5% and 47% in NCP, 38% and 45% in YRD, 47% and 48% in PRD, and 18% and 53% in ECH, respectively. The effects of control measures can be seen from the reduction in SO_2 and NO_2 concentration from PC[0] to PC[2]. In PC[2], SO_2 concentrations in NCP and YRD decrease by −28% and −9%, respectively; NO_2 concentration are same as those in 2005. However, even in PC[2], the SO_2 and NO_2 concentrations in PRD will increase by 16% and 11%, respectively.

3.3 Ozone concentration

Impacts of precursor emissions on the monthly mean of the daily 1-h maximum ozone concentrations are shown in Fig. 6. Due to the increase of future NMVOC emissions, the ozone concentrations are expected to increase by 4% in NCP, 12% in YRD, 5% in PRD, and 3% in ECH. Although in January, the increase of NO_x emission in REF[0] will reduce the ozone concentrations by −4% in NCP, −7% in YRD, −1% in PRD, and −1% in ECH. In July when ozone concentrations are high, the growth of NO_x emissions result in an increase in ozone concentrations by 4% in NCP, 6% in YRD, 3% in PRD, and 4% in ECH. The combined effects of NO_x and VOC emission growth on ozone concentrations are 8% in NCP, 12% in YRD, 9% in PRD and 8% in ECH. These results suggest that the effects of different ozone chemistry regimes in different seasons should be considered during policy-making for NO_x control. It is best to strictly control NO_x emissions during summertime (summer and fall in PRD) to obtain maximum ozone reduction benefits.

3.4 Particulate matter

Based on the stepped reductions of those five pollutants (i.e., SO_2, NO_x, NH_3, NMVOC and PM) from REF[0] to PC[2], the response of PM concentrations is shown in Fig. 7.

In REF[0], the $PM_{2.5}$ concentration will increase by 4% in NCP, 15% in YRD, 8% in PRD, and 8% in ECH. Under PC[2], the $PM_{2.5}$ concentration will decrease by 24% in NCP, 14% in YRD, 12% in PRD, and 18% in ECH.

Reduction of primary PM emissions plays the most important role in the decrease of $PM_{2.5}$ concentrations over China. The PM emissions in NCP, YRD, PRD and ECH are reduced by 19%, 14%, 16%, and 15%, respectively, in PC[2]. $PM_{2.5}$ concentration responses to the decrease of PM emissions are 1.5~1.8 in January and 1.8~3 in April, July, and October. $PM_{2.5}$ concentration is more sensitive to primary PM emissions in January due to lower atmospheric oxidation activities.

Increases in SO_2 emissions in REF[0] enhance $PM_{2.5}$ concentrations by 1% in NCP, 5% in YRD, 8% in PRD, and 3% in ECH; decreases in SO_2 emissions in PC[2] reduce the $PM_{2.5}$ concentrations by 5% in NCP, 1% in YRD, and 3% in ECH. Sensitivity of $PM_{2.5}$ concentrations to SO_2 emissions is largest in July with a scale of 3, and lowest in January with a scale of 10.

Growth of NO_x emissions also contributes to the increase in $PM_{2.5}$ concentrations. In REF[0], $PM_{2.5}$ concentrations are enhanced by 6%, 3%, 3% and 6% in NCP, YRD, PRD and ECH due to the increase in NO_x emissions. NO_x controls are more effective in April and July in NCP/YRD with an emission to concentration scale of 6~12, while are less effective in PRD with scale >20 due to NH_3-poor condition. The growth of NH_3 emissions contributes 2% to the increase of $PM_{2.5}$ concentration because of the increase in inorganic aerosol formation.

Impacts of NMVOC emission growth on $PM_{2.5}$ concentrations might only be seen in NCP and YRD in January,because of the increase in nitrate. It's hardly seen the impacts from NMVOC emission growth during summer when Secondary Organic Aerosol (SOA) should take relative large part of fine particles. The possible reason for this is the problem the CMAQ model has in simulating SOA.

SO_2 is the dominate sulfate species in $PM_{2.5}$. Because of the increase of SO_2 emissions in REF[0], sulfate concentrations will be enhanced by 4% in NCP, 21% in YRD, 26% in PRD, and 10% in ECH. In PC[2], impacts from stricter controls of SO_2 emissions will reduce sulfate concentration by 20% in NCP, 5% in YRD, and 11% in ECH, while sulfate concentration in PRD will slightly increase by 9%. The sensitivity of sulfate concentration to SO_2 emissions are higher in July, the scales are 1~1.5. The growth of NO_x emissions has positive impacts on the sulfate reduction because of the ozone chemistry, especially in January, April and October when VOC-limited regimes are dominating. Extra NO_x emission will react with OH to obstruct its reaction with SO_2 to generate sulfate; the reduction ratio of sulfate is 6%. Growth of NH_3 emissions contributes to a 6% increase in sulfate in YRD, and a 3% increase in the other three regions.

NO_x emissions are the dominate contributor to nitrate concentration in $PM_{2.5}$. Because of the increase of NO_x emissions in REF[0], the nitrate concentration will be enhanced by 28% in NCP, 24% in YRD, 32% in PRD, and 35% in ECH, especially in April and July when atmospheric oxidization is strong and the amount of biogenic VOC emission is large. In PC[2], which applied stricter controls on NO_2 emissions, the nitrate change ratios are 0% in NCP, −1% in YRD, 9% in PRD, and 2% in ECH. Nitrate concentration is more sensitive to NO_x emissions in NCP/YRD/ECH in July and in PRD in October with the scale of 1~1.5. NO_x emissions have less impacts on nitrate concentration in January with scale of 3~5. Growth of NMVOC emissions will enhance the nitrate concentration in January by 5% in NCP, 11% in YRD, and 1% in ECH. Growth of NH_3 emissions contributes to another 4%, 8%, 19% and 7% increase in nitrate in NCP, YRD, PRD and ECH, especially in July.

3.5 Total sulfur deposition and nitrogen deposition

The responses of total sulfur and nitrogen deposition to changes in precursor emissions are given in Fig. 9.

SO_2 emission is the dominant factor in total sulfur deposition. The relationship between SO_2 emission and sulfur deposition is nearly linear in nature. Because of the increase of SO_2 emissions in REF[0], total sulfur deposition will be enhanced by 4% in NCP, 32% in YRD, 37% in PRD, and 14% in ECH. In PC[2], impacts from stricter

controls on SO_2 emission will reduce total sulfur deposition by 24% in NCP, 8% in YRD, and 15% in ECH, with a slight increase of 13% in S-deposition in PRD. The linear regression coefficient for total sulfur deposition to SO_2 emission is around 1 for NCP/YRD in January, and for PRD in October, which indicates the sulfur deposition is wholly dependent on SO_2 emissions. The scale is 1.2~1.5 in April, October and July due to the impacts of an increase in ammonia emission.

Unlike nitrate, NH_3 emissions have a greater impact on the total nitrogen deposition, rather than NO_x emissions. This is because NH_3 can enhance the formation of nitrate and ammonium. Since NH_3 emissions will increase by 20% in 2020, the total nitrogen deposition will be enhanced by 16%, 17%, 16% and 12% in NCP, YRD, PRD and ECH. The increase of NO_x emissions in REF[0] will enhance the total nitrogen deposition by 7%, 10%, 14% and 11% in these areas. In PC[2], total nitrogen deposition will increase by 3% in PRD. The sensitivity of NH_3 emission to total nitrogen deposition are 1~1.3 in NCP, 1.2~1.5 in YRD, 1.3~2.7 in PRD, and 1.3~1.7 in ECH. In a similar manner, the impacts from NO_x emissions are relative small, with the scale of 5~8 in NCP and YRD, and 3~8 in PRD. Strong NO_x enhancements on total nitrogen deposition appear in NCP and YRD in April, and in PRD/ECH in January and October.

4 Conclusions

Because of the rapid growth of the economy and population, China's energy consumption by power plants and industries is predicted to double, and on-road transport is expected to be triple by 2020. Maintaining good air quality in China is a big challenge. It's urgent for the government to find possible solutions to reduce the primary emissions in order to protect people's health and the ecosystem. In this study, we've designed three control strategies leading up to 2020 based on a detailed step-by-step control implementation plan. Initially a more sustainable energy development strategy to improve energy efficiency needs to be adopted; this will bring a reduction in the emissions of SO_2, NO_x and PM_{10} by 4.1 Tg, 2.6 Tg, and 1.8 Tg, respectively. Second, better implementation of current control policies is needed and methods need to be adopted to ensure the emission sources meet the emission standard; this will reduce SO_2, NO_x and PM_{10} emission by 2.9 Tg, 1.8 Tg, and 1.4 Tg, respectively. Third, stricter policy standards need to be adopted to promote the applications of advanced control technologies; this will reduce SO_2, NO_x and PM_{10} emission by 3.2 Tg, 3.9 Tg, and 1.7 Tg, respectively.

Based on current control legislation and proposed control (as in REF[0]), the emission of SO_2, NO_x, VOC and NH_3 will increase by 17%, 50%, 49% and 18%, respectively, in 2020, while PM will be reduced by 10% over East China, compared to those in 2005. In the strict emission control scenario (PC[2]), the SO_2 and PM_{10} emissions will decrease by 18% and 38%, compared to those in 2005, while the NO_x and VOC emissions will increase by 3% and 8%, respectively. NH_3 emissions are kept at same level as those in 2005.

CMAQ simulations indicate that the concentration of SO_2 and NO_2 will increase by 5~47% and 45%~53% in REF[0]. The daily 1-h maximum concentration of ozone in summer will increase by 8%~12%. $PM_{2.5}$ concentrations will increase by 4%~15%, though primary PM emissions are significantly reduced. In addition, total sulfur depositions are predicted to increase by 4%~37%, and total nitrogen depositions will increase by 7%~14%.

Under the strict policy scenario PC[2], SO_2 and NO_2 concentrations will decrease by 16%~28% and 1%~11%, compared with 2005. $PM_{2.5}$ concentrations will be reduced by 24%~12%. Total sulfur deposition will also decrease by 13%~24%. However, because of the large NO_x emissions, ozone concentration in East China will slightly increase in summer. Total nitrogen depositions will also increase by 3%. Additional NO_x emission control policies need to be implemented to prevent the deterioration of the air quality in China, especially in those regions with a fast growing economy, such as PRD.

The individual impacts of SO_2, NO_x, NH_3, NMVOC and primary PM emissions on ozone and $PM_{2.5}$ concentrations have been analyzed. The results indicate the effects of different ozone chemistry regimes in different seasons.This information should be

considered in designing NO_x control policies. It is suggested to strictly control NO_x emissions during summertime (summer and fall for PRD area) to reduce ozone levels. In addition, NO_x emission controls are effective in reducing $PM_{2.5}$ levels in summer as well. While NH_3 has not been considered in the current air pollutant control strategy in China, its impact on $PM_{2.5}$ concentrations is important. In addtion, NH_3 emissions have significant impacts on total nitrogen deposition in the future. NH_3 emission controls should be considered as well.

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Table 1. Key parameters used in the development of energy scenarios.

	Scenario	2005	Reference Scenario [REF]	Policy Scenerio [PC]
Power plants (PP)	Electricity production (billion kW h^{-1})	2055	5226 (annual growth rate: 6.4%)	4759 (annual growth rate: 5.8%)
	Thermal efficiency	32.0%	37.5%	38.5%
	Percentage of coal power	95.2%	95.3%	93.6%
Industry (IND)	Energy consumption (PJ)	30 678	70 528 (annual growth rate: 4.1%)	66 155 (annual growth rate: 3.5%)
	Energy structure (ratio of coal, oil, gas and electricity)	59%, 10%, 11%, and 20%	57%, 9%, 14%, and 20%	54%, 9%, 16%, and 21%
Domestic (DOM)	Energy consumption (PJ)	16 333	21 786 (annual growth rate: 1.9%)	20 438 (annual growth rate: 1.5%)
	Energy structure (ratio of coal, gas, biomass, electricity and heat)	25%, 9%, 47%, 14%, and 4%	16%, 11%, 41%, 25%, and 7%	14%, 12%, 41%, 26%, and 7%
Transport (TRA)	Vehicle population of truck, car, and motor cycle (million)	9.55, 21.33 and 75.8	21.29, 136.7 and 98.0	
	Fuel economy of car, truck, motorcycle, and agriculture transport machine		Increase by 30%, 25%, 30%, and 15%	Increase by 40%, 36%, 36%, and 23%

Table 2. Sectoral fuel use by each Province in 2005 and 2020 scenarios (PJ).

Province	Power plant (PP)			Industrial boiler (IND)			Domestic (DOM)			On-road transport (TRA_RD)			Non-road transport (TRA_OTH)		
	2005	REF	PC	2005	REF	PC	2005	REF	PC	2005	REF	PC	2005	REF	PC
Anhui	700	1347	1195	799	1425	1315	756	617	562	99	229	218	128	164	162
Beijing	224	372	330	588	1193	1102	304	280	263	185	893	866	32	39	39
Chongqing	199	333	295	519	608	561	260	251	221	59	202	192	35	76	74
Fujian	445	1410	1251	722	1599	1474	131	236	210	80	252	242	33	35	34
Gansu	336	807	716	451	974	897	283	296	271	42	60	57	52	77	76
Guangdong	1801	5019	4451	1459	2484	2282	589	679	649	426	1382	1326	92	122	119
Guangxi	301	731	649	697	1956	1805	453	460	441	68	228	219	63	92	90
Guizhou	673	909	807	548	1629	1501	523	613	548	55	151	144	30	47	46
Hainan	74	235	208	85	173	160	164	136	128	19	76	72	8	11	10
Hebei	1498	3199	2837	3238	5038	4653	815	781	711	231	675	647	223	271	268
Heilongjiang	721	1096	972	926	949	876	476	365	347	97	225	216	67	95	94
Henan	1640	3363	2983	1487	3247	2993	754	681	622	173	461	442	209	241	239
Hubei	577	912	809	1175	1996	1842	728	591	540	102	252	241	94	137	134
Hunan	390	1126	999	1182	1032	953	617	501	458	93	211	202	98	142	138
Inner Mongolia	1346	4066	3607	970	2150	1983	476	690	622	78	210	201	59	64	64
Jiangsu	2137	5325	4723	2218	2627	2421	769	593	561	199	660	635	141	144	141
Jiangxi	392	922	818	521	1117	1030	278	245	221	60	196	187	53	77	76
Jilin	539	519	461	902	1112	1027	532	483	439	72	161	155	46	54	54
Liaoning	986	1731	1535	2185	2891	2669	609	753	682	153	394	378	80	112	110
Ningxia	318	1036	919	186	82	75	85	110	99	20	66	62	16	17	17
Qinghai	77	105	93	86	178	162	121	120	110	15	27	26	12	14	13
Shaanxi	530	1699	1507	368	368	339	394	365	332	70	210	201	49	55	54
Shandong	2198	4656	4129	3224	5592	5159	1533	1427	1314	273	956	917	244	284	278
Shanghai	782	1514	1343	695	1019	939	106	98	92	98	289	278	16	14	13
Shanxi	1395	2967	2632	1563	4634	4276	347	375	339	127	460	441	82	147	145
Sichuan	640	761	675	784	1493	1375	1255	1068	1000	153	411	394	74	134	130
Tianjin	366	426	378	552	1526	1408	121	105	98	66	213	206	27	36	35
Tibet	0	0	0	0	0	0	8	8	0	10	39	37	3	1	1
Xinjiang	319	678	601	815	2467	2280	256	301	270	66	158	152	32	48	47
Yunnan	449	634	562	771	1746	1611	368	333	304	127	247	237	45	66	64
Zhejiang	1098	2272	2015	1334	3263	3004	287	235	224	222	720	692	86	100	98
Total	23 151	50 172	44 501	31 051	56 570	52 170	14 397	13 796	12 680	3539	10 712	10 281	2228	2914	2861

Table 3. Penetration of selected air pollution control measures assumed under three control scenarios.

Sector	Sub-sector	Control technology	2005	2020 scenario		
				[0]-Baseline	[1]-Better implementation	[2]-Strict policy
Power plants	Old units	FGD(SO_2)	15%	45%	85%	85%
		LNB(NO_x)	46%	46%	100%	100%
	New units	FGD(SO_2)		100%	100%	100%
		SCR(NO_x)			45%	85%
		LNB(NO_x)		100%	100%	100%
	Grate boiler	CYC(PM)	40%	40%		
		WET(PM)	60%	60%	100%	
		ESP(PM)				85%
		FF(PM)				15%
	Pulverized coal boiler	WET(PM)	8%			
		ESP(PM)	92%	85%	85%	85%
		FF(PM)		15%	15%	15%
Industrial combustion	Grate boiler	FGD(SO_2)				30%
		LSC(SO_2)			50%	50%
		LNB(NO_x)				32%
		CYC(PM)	23%	6%		
		WET(PM)	73%	93%	100%	43%
		FF(PM)				57%
	Circulating Fluidized-Bed (CFB) boiler	LIN(SO_2)	100%	100%	100%	100%
		WET(PM)	100%	100%	100%	24%
		FF(PM)				76%
Domestic	Stove	LSC(SO_2)			80%	80%
	Boiler	LSC(SO_2)				80%
		CYC(PM)	23%	10%		
		WET(PM)	63%	83%	100%	84%
		FF(PM)				16%
Transport	Car-gasoline	Uncontrolled	39%			
		EURO-I	38%			
		EURO-II	23%	6%	6%	6%
		EURO-III		17%	17%	17%
		EURO-IV		78%	78%	13%
		EURO-V				65%
	Car-diesel	Uncontrolled	2%			
		EURO-I	59%			
		EURO-II	39%	3%	3%	3%
		EURO-III		10%	10%	10%
		EURO-IV		87%	87%	11%
		EURO-V				76%
	Trucks-diesel	Uncontrolled	33%			
		EURO-I	40%			
		EURO-II	27%	4%	4%	4%
		EURO-III		12%	12%	12%
		EURO-IV		11%	11%	11%
		EURO-V		73%	73%	73%
	Agriculture, construction machine	Uncontrolled	100%	100%	100%	
		EURO-I				13%
		EURO-II				12%
		EURO-III				41%
	Inland water	Uncontrolled	100%	100%	100%	
		EURO-I				13%
		EURO-II				32%

Notes: FGD: Flue Gas Desulfurization; LSC: low-sulfur coal; LIN: Limestone Injection into Furnace; SCR: Selective Catalytic Reduction; LNB: Low NO_x burner; CYC: mechanical dust collector; WET: wet dust collector; ESP: Electrostatic precipitation; FF: Fabric Filter

Table 4. Technology changes of selected industrial processes.

Sector	Technology	2005	2020
Power plants	Grate boiler	3.9%	1.7%
	Pulverized coal boiler	96.1%	98.3%
Industry boiler	Grate boiler	90%	85%
	Circulating Fluidized-Bed (CFB) boiler	10%	15%
Cement plant	Rotary kiln	4%	1%
	Vertical kiln	49%	7%
	Precalcining kiln	47%	91%
Lime plant	Earth kiln	70%	13%
	Modern kiln	30%	87%
Coke plant	Indigenous coke	8%	0%
	Machine coke	92%	100%

Table 5. Penetration of selected NMVOC control technologies in industry and solvents.

Sector	Sub-sector	Technology	Removal efficiency	VOC reduction in strategy-[2] compared to that in [0]/[1]
Industrial process	Chemical industry	Reduction of vent losses	70%	−21%
	Crude oil refineries	Inspection and maintenance; Install vapor recovery units	95%	−10%
	Coking plants			−70%
	Chemical pharmaceutical factory	End-of-pipe control technology	90%	−85%
	Vegetable oil extraction			−29%
Solvent use	Ink printing Paint use	Solvent management and substitution	50%∼100%	−64% −38%
	Glues and adhesives	End-of-pipe technology applied on new plants	90%	−30%
Fuel transport, storage and distribution	–	Install vapor recovery units	95%	−50%

Table 6. Changes of emission intensity in 2020 among regions and sectors (compared to 2005 level, %).

		North China Plain (NCP)				Yangtze River Delta (YRD)				Pearl River Delta (PRD)				East China (ECH)			
		REF	PC0	PC1	PC2	REF	PC0	PC1	PC2	REF	PC0	PC1	PC2	REF	PC0	PC1	PC2
SO_2	Power plant	−23	−33	−33	−33	−4	−17	−17	−17	37	22	22	22	−12	−23	−23	−23
	Industrial boiler	83	59	21	−11	134	100	54	14	143	92	67	46	98	69	29	−4
	Industrial process	2	2	2	−17	6	6	6	−11	−37	−37	−37	−41	4	4	4	−12
	Domestic	−24	−36	−41	−58	−76	−80	−80	−81	−56	−58	−58	−58	−22	−35	−39	−56
	Transportation	45	42	42	42	43	38	38	38	79	72	72	72	49	45	45	45
	ALL	**5**	**−7**	**−17**	**−27**	**36**	**19**	**5**	**−9**	**48**	**27**	**22**	**17**	**17**	**3**	**−7**	**−18**
NO_x	Power plant	65	45	20	−5	78	54	25	−1	126	101	66	33	81	59	32	4
	Industrial boiler	94	70	70	23	97	72	72	22	117	84	84	44	91	66	66	22
	Industrial process	35	35	35	22	36	36	36	22	31	31	31	17	34	34	34	21
	Domestic	−21	−30	−30	−30	−77	−80	−80	−80	−52	−54	−54	−54	−21	−31	−31	−31
	Transportation	0	−4	−4	−10	−1	−6	−6	−14	10	5	5	−3	1	−2	−2	−10
	ALL	**45**	**31**	**22**	**0**	**53**	**36**	**24**	**−1**	**62**	**47**	**35**	**14**	**50**	**35**	**25**	**3**
PM_{10}	Power plant	45	27	11	11	53	34	19	19	81	62	47	47	55	37	20	20
	Industrial boiler	91	70	64	−7	79	60	56	9	87	70	68	55	80	60	55	0
	Industrial process	−59	−59	−71	−72	−56	−56	−69	−71	−61	−61	−75	−75	−59	−59	−71	−72
	Domestic	−18	−26	−31	−34	−24	−35	−35	−35	−17	−22	−22	−22	−14	−23	−27	−29
	Transportation	−39	−40	−40	−43	−43	−45	−45	−49	−33	−34	−34	−40	−38	−39	−39	−41
	ALL	**−12**	**−19**	**−29**	**−42**	**2**	**−8**	**−17**	**−29**	**−16**	**−22**	**−31**	**−34**	**−10**	**−18**	**−27**	**−38**
VOC	Industry	141	141	141	35	148	148	148	55	162	162	162	50	139	139	139	43
	Domestic	−7	−7	−7	−15	93	93	93	58	2	2	2	−3	11	11	11	−1
	Transportation	−16	−16	−16	−16	−25	−25	−25	−25	−35	−35	−35	−35	−24	−24	−24	−24
	ALL	**50**	**50**	**50**	**5**	**87**	**87**	**87**	**34**	**47**	**47**	**47**	**4**	**49**	**49**	**49**	**8**
NH_3	**ALL**	**19**	**19**	**19**	**0**	**22**	**22**	**22**	**0**	**26**	**26**	**26**	**0**	**18**	**18**	**18**	**0**

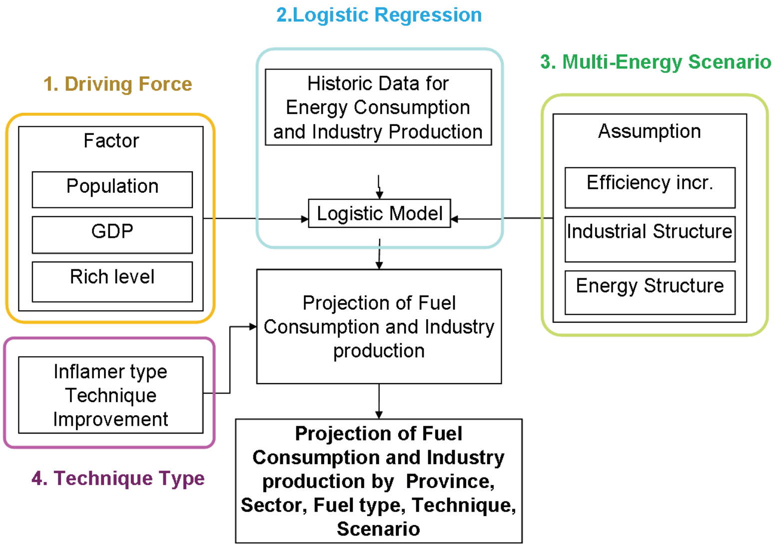
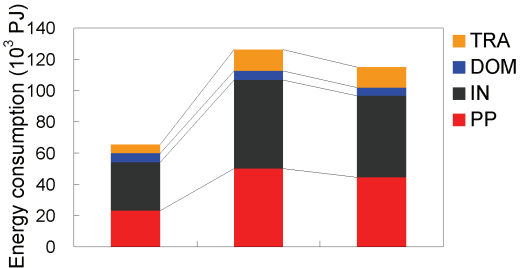
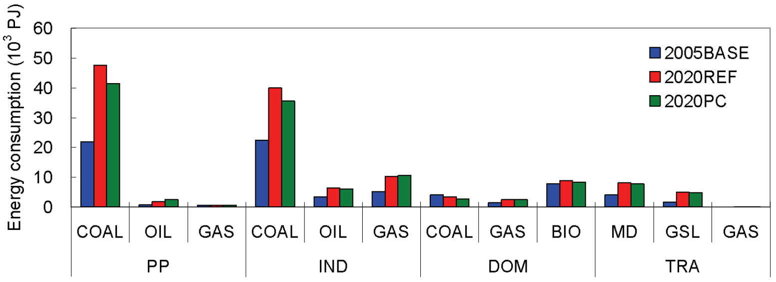


Fig. 1. Method of energy projection.

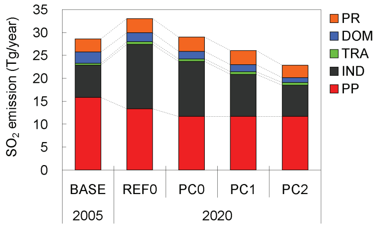


(a) Energy consumption by sectors in 2005 and 2020

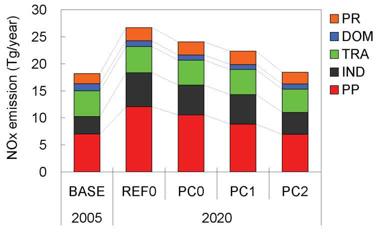


(b) Energy consumption by fuel type in 2005 and 2020

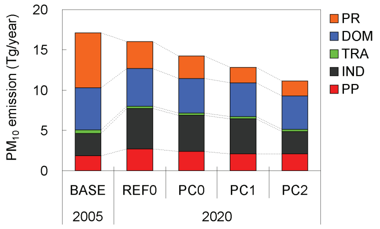
Fig. 2. Energy consumption in 2005 and 2020 (PP: power plants; IND: industry; DOM: domestic; TRA: transport).



(a) SO_2



(b) NO_x



(c) PM_{10}

Fig. 3. Contribution of each sector to total emissions in China (PP: power plants; IND: industry; DOM: domestic; TRA: transport; PR: industry process).

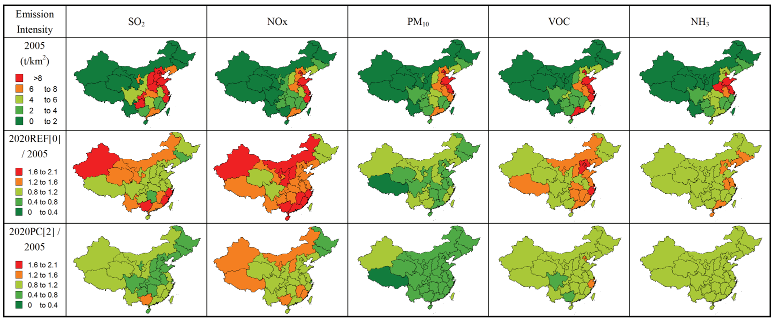
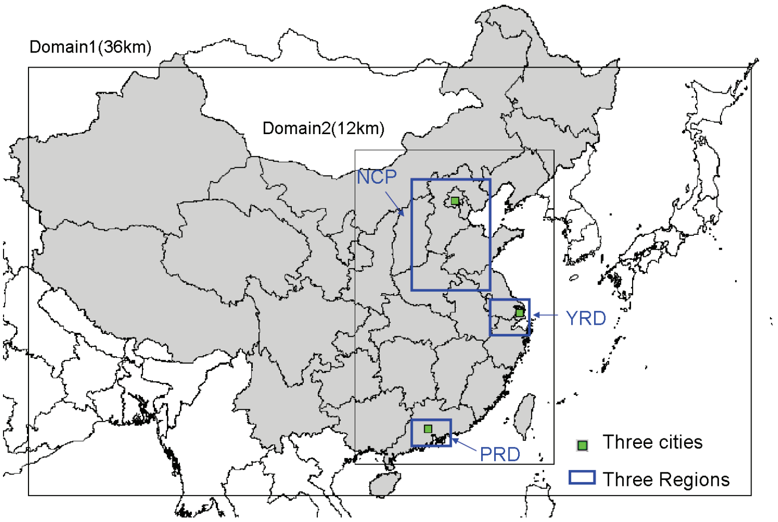


Fig. 4. Emission intensities of air pollutants in 2005 and 2020.



	Latitude, Longitude	Number of grids
North China Plain (NCP)	33~41° N, 112~119° E	4180 in domain 2
Yangtze River Delta (YRD)	30~32° N, 119~123° E	682 in domain 2
Pearl River Delta (PRD)	21~24° N, 112~115° E	625 in domain 2
East China (ECH)	20~44° N, 106~127° E	29 104, the whole domain2

Fig. 5. Modeling domain and location of three regions.

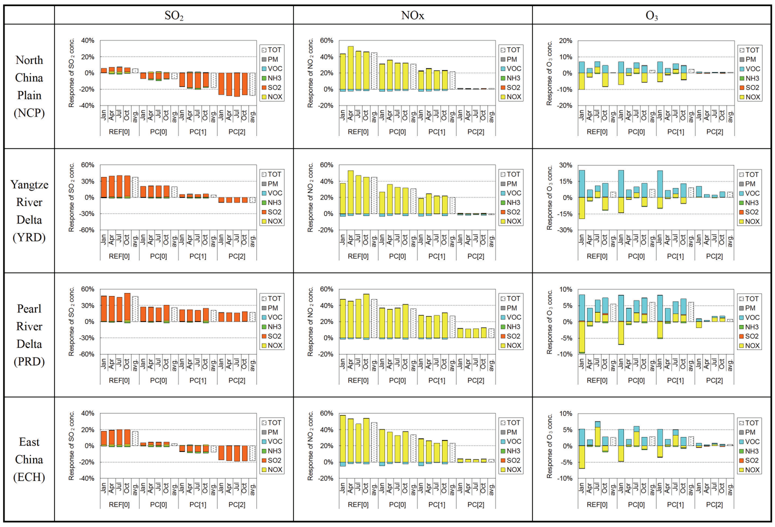


Fig. 6. Responses of gas species to emission changes in 2020 (monthly average for SO_2 and NO_2, monthly mean of daily 1-h maxima for O_3).

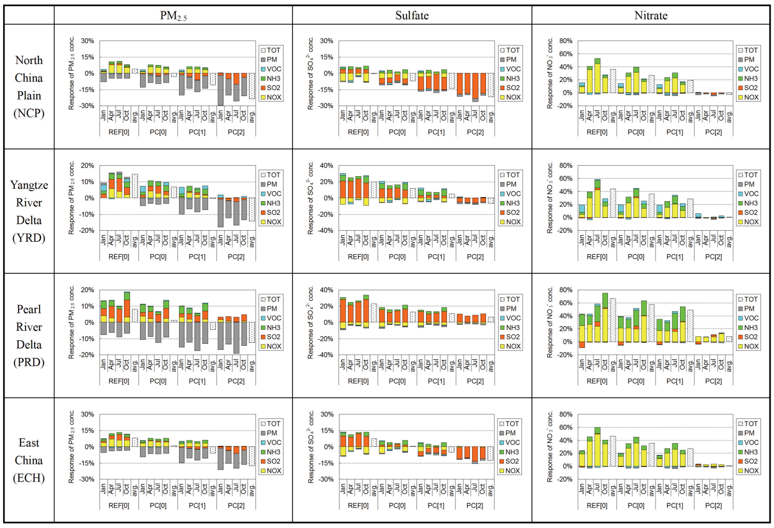


Fig. 7. Responses of PM concentrations to emission changes in 2020 (monthly average).

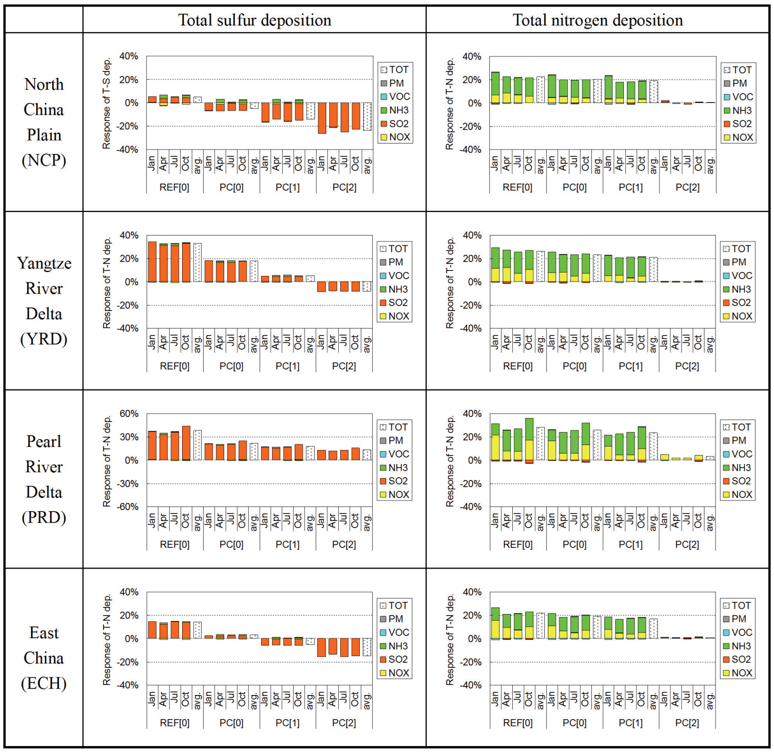


Fig. 8. Responses of S/N-deposition to emission changes in 2020 (monthly average).