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Discussions

The effects of energy paths and emission controls and standards on future trends in China's emissions of primary air pollutants

Y. Zhao[1], J. Zhang[2], and C. P. Nielsen[3]

[1]State Key Laboratory of Pollution Control and Resource Reuse and School of the Environment, Nanjing University, 163 Xianlin Ave., Nanjing, Jiangsu 210023, China
[2]Jiangsu Provincial Academy of Environmental Science, 241 West Fenghuang St., Nanjing, Jiangsu 210036, China
[3]Harvard China Project, School of Engineering and Applied Sciences, Harvard University, 29 Oxford St, Cambridge, MA 02138, USA

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Correspondence to: Y. Zhao (yuzhao@nju.edu.cn)

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Abstract

To examine the efficacy of China's actions to control atmospheric pollution, three levels of growth of energy consumption and three levels of implementation of emission controls are estimated, generating a total of nine combined activity-emission control scenarios that are then used to estimate trends of national emissions of primary air pollutants through 2030. The emission control strategies are expected to have more effects than the energy paths on the future emission trends for all the concerned pollutants. As recently promulgated national action plans of air pollution prevention and control (NAPAPPC) are implemented, China's anthropogenic pollutant emissions should decline. For example, the emissions of SO_2, NO_x, total primary particulate matter (PM), PM_{10}, and $PM_{2.5}$ are estimated to decline 7 %, 20 %, 41 %, 34 %, and 31 % from 2010 to 2030, respectively, in the "best guess" scenario that includes national commitment of energy saving policy and partial implementation of NAPAPPC. Should the issued/proposed emission standards be fully achieved, a less likely scenario, annual emissions would be further reduced, ranging from 17 % (for primary $PM_{2.5}$) to 29 % (for NO_x) declines in 2015, and the analogue numbers would be 12 % and 24 % in 2030. The uncertainties of emission projections result mainly from the uncertain operational conditions of swiftly proliferating air pollutant control devices and lack of detailed information about emission control plans by region. The predicted emission trends by sector and chemical species raise concerns about current pollution control strategies: the potential for emissions abatement in key sectors may be declining due to the near saturation of emission control devices use; risks of ecosystem acidification could rise because emissions of alkaline base cations may be declining faster than those of SO_2; and radiative forcing could rise because emissions of positive-forcing carbonaceous aerosols may decline more slowly than those of SO_2 emissions and thereby concentrations of negative-forcing sulfate particles. Expanded control of emissions of fine particles and carbonaceous aerosols from small industrial and residential sources is recommended, and a more comprehensive emission control strategy tar-

geting a wider range of pollutants and taking account of more diverse environmental impacts is also urgently needed.

1 Introduction

Attributed to the large size and rapid growth of its economy and energy consumption, China's emissions of key primary atmospheric pollutants (SO_2, NO_x, and particle matter, PM) are now estimated to be the highest in the world (Klimont et al., 2009; Lu et al., 2010; Lei et al., 2011a; Y. Zhao et al., 2013; B. Zhao et al., 2013). For example, China's SO_2, NO_x and $PM_{2.5}$ emissions in 2010 were estimated at 27.7, 29.0, and 12.3 terrograms (Tg) (Y. Zhao et al., 2013), accounting for 32 %, 31 %, and 31 % of global emissions, respectively (Cofala et al., 2012). Such high emissions have led to poor air quality (Richter et al., 2005; van Donkelaar et al., 2010; Lin et al., 2010) and various environmental impacts including public health damage (WB and SEPA, 2007; Parrish and Zhu, 2009; Kan et al., 2012; Matus et al., 2012) and ecosystem acidification (Larssen et al., 2006; Zhao et al., 2009, 2011a).

To alleviate serious air pollution and the resulting environmental impacts, China has conducted a national strategy of energy conservation and emission reduction since 2005. Compulsory control measures are required in major economic sectors to limit fossil energy inputs and high emissions. These measures include replacement of small and inefficient plants or boilers with larger and energy-efficient ones in the power and some other heavy industrial sectors; installation of flue gas desulfurization (FGD) systems at all newly-built and many pre-existing thermal power units; and staged implementation of more stringent emission standards on vehicles. The strategy has proven effective: national emissions of SO_2 and PM are estimated to have declined gradually from 2005 to 2010 (Lu et al., 2011; Y. Zhao et al., 2013), partly confirmed by satellite and ground observation (Li et al., 2010; Y. Zhao et al., 2013). Urban air quality, particularly leading up to and during major events (e.g., Beijing Olympics and Shanghai Expo), was improved due to incrementally tightened emission control and closures or relocations of major industrial plants (Wang et al., 2009, 2010). These measures, however, failed to restrain the growth of NO_x emissions that are critical to formation of $PM_{2.5}$ and O_3 in the atmosphere. Episodes of extremely severe regional haze have occurred more frequently in recent years and have become a growing concern (Zhang et al., 2012a; Ma et al., 2012; Wang and Hao, 2012; Wang et al., 2013, 2014), illustrating the need for expanded efforts in pollution control. Facing these circumstances, the government in succession issued new national ambient air quality standards (NAAQS) and a national action plan of air pollution prevention and control (NAPAPPC), requiring expanded and intensified efforts at emission abatement and air quality improvement. Since 2010, the national emission standards have been updated or proposed across a number of sectors, with much tighter emission limits overall.

The implementation of above-mentioned measures and standards will significantly affect the source characteristics and emission level of the primary air pollutants that substantially determine regional air quality. The future trends in emissions of individual pollutant species and their interactions are important not only to understanding the physical and chemical cycles of air pollutants but also to evaluating the effectiveness and informing the design of policy strategies on air quality and even climate, using chemical transport models. A number of analysts have predicted future trends of China's air pollutant emissions (Ohara et al., 2007; Klimont et al., 2009; Xing et al., 2011; B. Zhao et al., 2013). Most studies except very recent ones (e.g., B. Zhao et al., 2013), however, have little detailed analyses on the effects of ongoing or upcoming control measures on the trends in emission factors (the emission levels per unit energy input or product output) by source type. In particular, the potential benefits of newly issued emission standards across sectors have not been well quantified, raising uncertainty of current estimates.

In this study, different scenarios of emission control and energy consumption in China are designed and the future emissions of SO_2, NO_x and PM in different size classes (Total Suspended Particles (TSP), PM_{10}, and $PM_{2.5}$) are correspondingly estimated, including careful analyses of the changes in emission factors due to implementation of various control measures across sectors. It focuses on the period from 2010 to 2030, during which current plans anticipate most of China's megacities to meet the new NAAQS issued in 2012. Section 2 reviews the bottom-up emission inventory methodology and briefly describes the scenarios applied in this work. Section 3 is a thorough analysis of future trends of emission factors and their driving forces by sector, incorporating the latest information of emission control strategies and standards and data from domestic field measurements and investigations. Section 4 presents the predicted future emissions of primary air pollutants by scenario, and related discussions including the effectiveness of the emission control strategy, the implications of the interaction of different pollutant trends to ecosystems and climate forcing, and comparisons with other studies. Section 5 summarizes the study.

2 Methods

2.1 The source categories of the emission inventory

The research domain covers the 31 provinces of mainland China (see Fig. S1 in the Supplement). All main anthropogenic activities are included in the emission inventory framework. At the most aggregated scale, sources fall into four main sector categories: coal-fired power plants (CPP), all other industry (IND), transportation (TRA, including on-road and non-road subcategories), and the residential and commercial sector (RES, including fossil fuel, biofuel use, and biomass open burning subcategories). IND is further divided into cement production (CEM), iron and steel plants (ISP), brick production (BRI), lime production (LIM), nonferrous metal production (NMP), and other industrial boilers and non-combustion processes (OIN), reflecting the structure of available data. The detailed methods of developing a bottom-up emission inventory for SO_2, NO_x and PM are described in previous studies (Zhao et al., 2011b; Y. Zhao et al., 2013). Generally, annual anthropogenic emissions of those pollutants are estimated by sector using

Eq. (1):

$$E_{i,t} = \sum_{k}\sum_{m}\sum_{n} \mathrm{AL}_{k,m,n,t} \times \mathrm{EF}_{i,k,m,t} \times R_{k,m,n,t} \times (1 - \eta_{i,n,t}) \tag{1}$$

where i, k, m, n and t stand for species, sector, fuel type, emission control technology and year, respectively; AL is the activity level, either energy consumption or industrial production; EF is the unabated emission factor; R is the penetration rate of a given emission control technology; and η is the removal efficiency of that technology.

2.2 Scenarios and activity levels

The year 2010, for which the authors estimated the emissions previously (Y. Zhao et al., 2013), is set as the base year, and annual emissions of SO_2, NO_x, and PM are predicted for 2015, 2020, and 2030 based on different scenarios. To better understand the effects of activity levels (e.g., fuel consumption and industrial production) and emission control strategies on future emission trends, three levels of growth of energy and industrial production (explained later in this section) and three levels of implementation of emission controls (explained in details in Sect. 3) are considered. This generates a total of nine combined activity-emission control scenarios evaluated for each of the target years. Table 1 summarizes the general assumptions about the energy trends and emission control polices and the derived scenarios.

Regarding activity levels, the principles behind scenarios of the International Energy Agency (IEA, 2012) are followed in this work, resulting in a Current Policy Scenario (CPS), a New Policy Scenario (NPS), and a 450 Scenario (450S). The assumptions of the three energy scenarios are explained in detail by IEA (2012). Briefly, as indicated in Table 1, NPS is identified as the "best guess" of future energy trends, taking account of the national energy policy commitments that have been announced (e.g., the plans to reduce fossil energy use and to reduce greenhouse gas emissions). In comparison, CPS is a conservative estimate that assumes those commitments will not be implemented and the national energy policy will not change in practice after 2010. The

450S is an aggressive scenario, which sets a Chinese energy path (as part of a global strategy) to limit the concentration of greenhouse gases in the atmosphere to around 450 ppm of CO_2 equivalent.

The current study applies most of the activity levels projected by IEA (2012) for all the scenarios, with some revisions for given emission sources based on more recent domestic information, as described below. Electric power generation is China's biggest coal-consuming sector, and since 2005 the government has implemented a series of measures to improve energy efficiency and to conserve coal use in the sector. Small and inefficient units have been scheduled for staged shutdown, first those less than 100 MW and then up to 200 MW. In this work, two steps are used to predict future coal consumption by power plants. First, the coal use of "old" units (i.e., those built before the end of 2010) are estimated based on the detailed power unit database compiled by the authors (Zhao et al., 2008) and the government measures to phase out small units. These include assuming the retirement of: all pulverized-coal units less than 100 MW and grate units for electricity generation only (i.e., not including combined heat and power units, CHP) by 2015; all units less than 200 MW for electricity generation only by 2020; and all CHP units less than 200 MW by 2030. These actions lead to total capacities of old units of 588, 579, and 555 GW for 2015, 2020, and 2030, respectively, and coal consumption for these units at 1265, 1246 and 1179 million metric tons (MMT). Second, the growth of "new" units (i.e., those built after 2010) is predicted based on the power plant construction plans by the State Grid. In the reference plans made in 2013, the average growth of national capacity is estimated at 50 GW year^{-1} from 2010 to 2020 and 30 GW year^{-1} from 2020 to 2030 (internal data, unpublished), and this assumption is applied in the CPS scenario in this work. Regarding NPS and 450S, the total thermal capacity is reduced due to slower increases in electricity demand and more penetration of renewable power, as analyzed by the authors previously (Zhao et al., 2008). The coal consumption paths are thus projected based on the capacity, average coal use per unit generation of electricity (320 gce kWh^{-1}), and the average annual operation hours (4700 h, personal communication with the director of the China

Electricity Council). Table 2 lists the total capacities and coal consumption of power plants projected in this work, compared with those by IEA (2012). In most cases (except 450S for 2020 and 2030), IEA has less capacity but higher coal consumption, likely due to less consideration of improved coal combustion efficiency and reduced running hours for China's power units in the future.

The energy use (coal, oil, natural gas, and biofuel) of industry and residential and commercial sectors are taken from the IEA projection. It should be noted, however, that the total industry sector in this work is further divided into several subcategories to get better understanding of the emission trends of those sources. Therefore, the coal consumption of CEM, ISP, LIM, and BRI, which depends on the output of relevant industrial products, must be estimated and then subtracted from the total industrial consumption to derive the coal use from other industrial boilers (OIN), for which sufficient independent data are lacking. The cement and steel production is projected by IEA. The differences between scenarios are very small, e.g., the cement production in 2030 is estimated at 1972, 1954, and 1947 MMT for CPS, NPS, and 450S, respectively. IEA does not project lime and brick production, for which activity levels are also less developed in China's emission inventory literature (Zhao et al., 2011b). In this work, therefore, a rough estimate is made that the relative changes in lime and brick production in all scenarios follow those of cement in NPS. The coal consumption of those industrial processes is then calculated following the methods described in previous studies (Zhao et al., 2011b, 2012). In particular, it should be noted that coal consumption will be influenced by technology changes of emission sources, and that fact is considered in the activity level estimation by sector. For example, precalciner kilns consume 30 % less coal than rotary ones for the same amount of cement production (Lei et al., 2011a), and production of solid clay bricks requires twice the coal consumption of hollow ones (Zhao et al., 2012). The details of technology changes by sector will be explained in Sect. 3. Figure 1a summarizes the coal consumption by source and scenario for 2015, 2020, and 2030 estimated in this work.

The future oil consumption by the transportation sector is a big concern in China's energy research and has been addressed by a series of studies (Wang et al., 2006; Huo et al., 2012a; Ou et al., 2010; IEA, 2012). Compared to IEA (2012), Huo et al. (2012a) incorporated the latest data from investigation of the fuel economy and intensity of use of China's vehicles. Thus the oil consumption of on-road and rural vehicles in the high- and low-vehicle-growth scenarios by Huo et al. (2012a) are applied in this work, replacing the data of the original CPS and NPS by IEA (2012). For 450S, we keep the values of IEA (2012) as the most aggressive case for energy conservation. Regarding non-road sources, the diesel consumption of railways and inland ships is adopted from IEA; for other off-road equipment, the growth rates after 2010 are taken from an assumption in a recent domestic study (Li, 2011). Figure 1b summarizes the future oil consumption from China's transportation sector by source and fuel type for different scenarios. With revisions based on the various aforementioned sources, the difference between CPS and NPS in this work tends to be larger than that in IEA (2012).

3 Emission factor projection

With such an expansive and complex emission category structure, the emission characteristics vary largely across both individual sources and sectors in China. Current and future emission control measures under the NAPAPPC and possible implementation of new emission standards for given sectors are expected to further change the penetration levels of different energy efficiency technologies and emission control devices, and thus to significantly affect the emission factors of primary pollutants. Therefore, quantification of the potential trends of emission factors by source is crucial for projecting national emissions and is thereby the primary undertaking of this study. A base case (BAS), a reference case (REF), and a case of fully implemented emission standards (STD) are applied, as summarized in Table 1. In BAS, the emission control levels for each given technology are conservatively assumed unchanged in the future. This does not imply, however, that the penetration levels of advanced technologies and emission control devices for a whole subsector or sector will necessarily be the same as in the base year 2010. For example, the policy of replacing small power units with bigger and cleaner ones will undoubtedly raise the application of flue gas desulfurization (FGD) systems for the power sector overall, even if the FGD application rates for small and large units remain at 2010 levels. REF is set as the "best guess" in terms of emission control strategies for the future. The proposed polices and possible new improvements in emission control according to the NAPAPPC are included in the scenario and their benefits are analyzed with currently available domestic information. STD is a case assuming that the series of emission standards for sources across power and industrial sectors that China has issued or updated since 2010 will be strictly enforced (these standards are listed in Table S1 in the Supplement). Accordingly, STD is an aggressive control strategy. The trends of emission factors by source and scenario are analyzed in detail below and summarized in Fig. 2.

3.1 Coal-fired power plants

Since 2005, coal-fired power plants have been targeted for the most stringent emission controls, and the capacity shares of big power units (≥ 300 MW) and FGD systems reached 78 % and 86 % at the end of 2010, respectively, leading to great SO_2 and PM emission reductions (Y. Zhao et al., 2013). For NO_x control, the capacity share of selective catalytic reduction (SCR) technology was still small at 13 % in 2010, and another 100 GW of SCR systems are under construction (Wang, 2013). The future emission trend depends largely on the penetration and removal efficiency of those technologies.

In BAS, the emission control strategies for the power sector in 2010 are assumed to continue, i.e., FGD systems will be required at all new power units and the national average of SO_2 removal efficiency will remain 70 %, consistent with the results of a national survey of emission sources conducted in 2007 (Y. Zhao et al., 2013); no additional penetration of SCR is expected.

REF assumes a higher (80 %) SO_2 removal efficiency of FGD systems, due to improved operations, as indicated by recent investigation of power plants by the authors (unpublished; see Table S2 in the Supplement). It also assumes SCR technologies are required for all newly built units and “old” ones (i.e., those built before the end of 2010) equal to or bigger than 300 MW in “key” regions (i.e., those with relatively concentrated industry and heavy pollution; these are eastern, north-central, and south-central China in this work, shown in Fig. S1 in the Supplement). For old units located in other areas, selective non-catalytic reduction (SNCR) technology is assumed, which has lower cost but also lower benefits of NO_x control. The penetrations of different technologies by scenario and year are indicated in Fig. S2a in the Supplement. The average NO_x removal efficiencies for SCR and SNCR are cautiously set at 60 % and 50 %, respectively, less than those of full operation (personal communication with China Electricity Council director). For PM control, increased penetration of fabric filter (FF) or electrostatic-bag dust collectors is assumed, accounting for one-third of newly built unit capacity (see Fig. S3a for the trends of dust collector shares). All of the unabated emission factors and PM removal efficiencies for various types of dust collectors are obtained from the power plant emission factor database compiled by the authors (Zhao et al., 2010; see also Table S2 in the Supplement).

In STD, the new national emission standard for power plants issued in 2011 (GB 13223-2011) is applied to determine the emission factors of power units. Since the standard requires all of the units with different ages to satisfy the same emission limits at the beginning of 2014, the emission levels of SO_2, NO_x, and PM are simply set to the standard limits of 200, 200, and 30 $\mathrm{mg\,m^{-3}}$ respectively for 2015 and after, and the emission factors ($\mathrm{kg\,t^{-1}}$) can then be derived following the method provided by Zhao et al. (2010). There are no specific limits for PM differentiated by size class, thus the mass fractions of PM_{10} and $PM_{2.5}$ to PM are respectively assumed to be 0.81 and 0.45, based on the field measurement results of power units with FF that can achieve the emission standard for total PM (Zhao et al., 2010). This method will also be applied for other source types in similar case to determine the PM_{10} and $PM_{2.5}$ mass fractions in STD. As shown in Fig. 2a, NO_x emission factors are expected to decrease fastest of the three pollutants in REF and STD, reflecting the intended benefits of the country's NO_x control measures in the future.

3.2 Cement production

At the end of 2010, China's cement production was dominated by precalciner kilns, the most energy-efficient technology, with the share exceeding 80 % (Y. Zhao et al., 2013). Although the PM emission control performance of precalciner kilns is strong due to high penetration of FF (as shown in Fig. S3b in the Supplement), they are liable to generate more NO_x emissions because of higher combustion temperatures than other types of kilns (Lei et al., 2011b). In BAS, all of the cement plants built after 2010 are assumed to use precalciner kilns but without requirement of additional NO_x control, such as SCR/SNCR systems. In REF, all non-precalciner kilns are assumed to be entirely shut down by 2020 and application of SNCR, with the NO_x removal efficiency tentatively set at 50 %, is assumed for precalciner kilns in the aforementioned key regions after 2010. For kilns in other areas, low-NO_x burners (LNB) are assumed to be used after 2015, with lower NO_x control effect (see the penetrations and removal efficiencies of those systems in Fig. S2b and Table S2 in the Supplement, respectively). Although the new emission standard for cement production has not yet been issued, a reduction in the NO_x standard from 800 to 400 $\mathrm{mg\,m^{-3}}$ has been proposed (unpublished), leading to a reduced average emission factor of 1.2 kg $NO_x\,t^{-1}$ clinker. Based on the assumption that 1 ton of cement is produced from 0.72 tons of clinker, and that production of 1 ton of cement requires 125 kg of coal in precalciner kilns (Lei et al., 2011b), the NO_x emission factor of the proposed limit is calculated at 6.8 $\mathrm{kg\,t^{-1}}$ coal, and applied in STD of this work. Given the time needed for standard implementation, however, the old plants (defined as those built before the end of 2010) are assumed to satisfy the limit from 2020 on. All of the other unabated emission factors of SO_2, NO_x, and PM and the PM removal efficiencies of dust collectors are taken from the country-specific database compiled by Lei et al. (2011b) and Zhao et al. (2011b). As seen in Fig. 2b, PM emission factors in REF and STD will keep declining due to additional penetration of FF, and the NO_x limit of the proposed standard could be approached by use of SCR systems, even without full operation of the technology.

3.3 Iron and steel production

The emissions of the iron and steel industry include mainly gaseous and particle pollutant emissions from coking, sintering, pig iron-making (in blast furnaces), and particle emissions from steel-making (nearly 90 % of which occurs in basic oxygen furnaces) and casting processes. In this work, we assume that the shares of various types of dust collectors would remain the same as those in 2010 for all processes in BAS, while new emission sources (reflected by the annual net growth of production) would apply the most advanced dust collectors that have already been deployed in analogous processes in REF, reflecting the effect of national policies to foster energy conservation and emission reduction. This assumption leads to strong reduction of PM emission factors of iron and steel production in REF compared to those in BAS (Fig. 2c), and it will still hold for other industrial sources described in Sect. 3.4 (see Fig. S3c–k in the Supplement for detailed information on penetration levels of various dust collectors in iron and steel production and other industrial processes). The unabated PM emission factors and removal efficiencies of dust collectors used in BAS and REF are taken from a previous study by the authors (Zhao et al., 2011b).

For coke production, the emission factors are updated to 1.0 (machinery coking ovens)–4.3 $\mathrm{kg\,t^{-1}}$ coke (indigenous ovens) for SO_2 and 1.7 $\mathrm{kg\,t^{-1}}$ coke for NO_x, based on recent domestic measurements (He, 2006; Huo et al., 2012b). The emission factors used for STD are determined based on the emission standard of pollutants for the coking chemical industry issued in 2012 (GB 16171-2012), which sets the same emission limits for 2015 and beyond for both newly built and existing ovens. For example, the SO_2 concentration in flue gas is limited at 50 $\mathrm{mg\,m^{-3}}$ for machinery coking ovens, equal to 0.24 $\mathrm{kg\,t^{-1}}$ coke based on an average of flue gas volume at 5.0 $\mathrm{N\,m^3\,kg^{-1}}$ coke

(He, 2006). The big reduction of emission factors from REF to STD would force adoption of FGD in coke production to achieve sufficient removal efficiency. Similarly, the NO_x and PM emission factors for machinery coking are calculated at 2.4 and 0.3 $kg\,t^{-1}$ coke, respectively.

Based on domestic measurements (AISGC, 2007; MEP, 2010), the SO_2 and NO_x emission factors for sintering processes were respectively estimated at 2.9 and 1.3 $kg\,t^{-1}$ product, as used in previous work (Y. Zhao et al., 2013) and in the BAS of this study. Under REF, adoption of FGD systems is assumed for sintering, with the mean removal efficiency of SO_2 conservatively set at 50 % according to limited field investigation by the authors in 2012 (unpublished). As a result, the SO_2 emission factor for the whole iron and steel sector will be significantly reduced, as sintering is the main source of SO_2 emissions in the sector (Fig. 2c). However, no extra measure for NO_x control is assumed to be implemented. The STD emission factors are determined based on emission standards of air pollutants for sintering and pelletizing issued in 2012 (GB 28662-2012), i.e., 0.7, 0.8, and 0.25 $kg\,t^{-1}$ product for SO_2, NO_x, and PM, respectively.

For blast-furnace iron production, a national survey (MEP, 2010) determined current averages of emission factors for SO_2 and NO_x of 0.15 and 0.20 $kg\,t^{-1}$ iron, respectively, as applied in previous work (Y. Zhao et al., 2013) and BAS and REF of this study. Regarding STD, domestic plants with the highest energy efficiencies and most advanced emission control technologies were investigated (SSC, 2007) and the emission factors of 0.05, 0.10, and 0.12 $kg\,t^{-1}$ iron for furnace SO_2, NO_x, and PM are determined and finalized as the emission standards for air pollutants from the iron smelting industry (GB 28663-2012). The mass fraction of PM_{10} and $PM_{2.5}$ in STD are estimated based on the removal efficiencies of FF by particle size. The fugitive PM emissions, however, are difficult to quantify for STD and are assumed to be the same as REF. For steel-making, very little SO_2 or NO_x is emitted from basic oxygen/electric furnaces. According to a national investigation (BGC, 2007), the PM emission levels of big plants with improved emission control are around 60 % lower than the national average and set as the limit of the emission standard for the steel smelting industry (GB 28664-2012) and thereby assumed as the emission factor of STD in this work.

The casting process also generates particles. However, there is no clear emission standard or other information about emission control for the process yet. Therefore we assume the same PM emission factors in STD as those in REF of this work.

3.4 Other industrial sources

Emission factors of brick production, lime production, nonferrous metal smelting, and other boilers are described in this section.

Coal combustion in kilns is the main source of SO_2 and NO_x emissions in brick production. In the base year 2010, solid bricks accounted for around 40 % of total production and the national average of coal consumption per 10 000 bricks are estimated at 0.88 metric ton equivalent (tce), based on the coal consumption rates of 1.3 tce/10 000 solid clay bricks and 0.6 tce/10 000 hollow ones (Xu and Wang, 2007; Zhao et al., 2012). According to a national survey of brick kilns (CRAES, 2009), the average SO_2 and NO_x emission levels are 345 and 160 $mg\,m^{-3}$ in flue gas, respectively, and the emission factors can then be calculated at 17 and 8.0 kg/10 000 bricks based on the average flue-gas amount of ~ 50 000 $N\,m^3$/10 000 bricks, i.e., 14.0 and 6.5 $kg\,t^{-1}$ coal, respectively. We assume the fraction of solid bricks unchanged in BAS, and thus the SO_2 and NO_x emission factors remain the same as in 2010. In REF, however, the use of solid bricks is assumed to be strictly limited at the 2010 level and the coal consumption per 10 000 bricks decreases accordingly, leading to a lower level of SO_2 and NO_x emission levels, as shown in Fig. 2d. Regarding PM, as mentioned in Sect. 3.3, the penetration of various types of dust collectors and thereby the emission factors for BAS are assumed the same as that in 2010 (Y. Zhao et al., 2013), but more application of wet scrubbers with higher PM removal efficiency than cyclones is expected in REF, resulting in a considerable reduction of PM emission factors. For STD, as proposed in the new standard (CRAES, 2009), the PM limit is set roughly 80 % lower than current level, while no significant reduction is required for SO_2 or NO_x. The mass fraction of

PM_{10} and $PM_{2.5}$ are determined based on the size-dependent removal efficiencies of wet scrubbers.

Until now there is little information about nor any proposed standard for emission control in lime production. The emission factors for SO_2 and NO_x in base year 2010 are applied for all scenarios in this work. PM emission factors for BAS remain the same as the base year, while they are expected to decline in REF and STD, attributed to increased penetration of FF with higher PM removal efficiencies.

Nonferrous metals include production of copper (Cu), lead (Pb), zinc (Zn), electrolytic aluminum (Al) and alumina that generate SO_2 and PM emissions. For SO_2, a national survey was conducted (MEP, 2010), based on which the current level, the emission limit for existing sources, and the limit for newly built sources, are determined and applied for emission factors of BAS, REF, and STD in this work, respectively. For Cu smelting, as an example, the current average level of flue-gas SO_2 concentration, the limit for existing sources, and the limit for the new sources was estimated at 2116, 960, and 400 $\mathrm{mg\,m^{-3}}$, and the emission factors of BAS, REF, and STD can then be accordingly calculated at 49, 22, and 9 $\mathrm{kg\,t^{-1}}$ Cu, respectively, based on the average flue gas amount of 23 000 $\mathrm{N\,m^3\,t^{-1}}$ Cu (CRAES, 2007; MEP, 2010). The PM emission factors of BAS are assumed the same as in the base year (Y. Zhao et al., 2013) and those of REF are expected to decrease due to more application of advance dust collectors. For STD, the newly issued emission standards for nonferrous metals (GB 25465-2010; GB 25466-2010; and GB 25467-2010) requires significantly enhanced control and the extremely low limits imply the need to apply the most effective dust collectors like FF. Compared to BAS, roughly 80 % of emission abatement is required by the standards for both SO_2 and PM (Fig. 2e).

For other industrial coal-combustion boilers, the emission factors in BAS are assumed to be the same as 2010. In REF and STD, FGD and LNB are expected to be used for newly-built sources following the instructions of the NAPAPPC with the average SO_2 and NO_x removal efficiencies of 70 % and 30 %, respectively. Figure S2c in the Supplement respectively shows the penetrations of those technologies in detail.

For PM control, similar with other industrial sources, the new sources are expected to be installed with wet scrubbers, leading to reduced PM emission factors. The emission factors of oil and gas boilers are assumed to remain the same as 2010 for all the scenarios.

3.5 Transportation

China's new on-road vehicles have been required to meet staged emission standards (Stage I–IV, equivalent to Euro I–IV) since 1999. Based on the vehicle population growth and assumed vehicle lifetimes by type, the fleet compositions by control stage can be determined and thus the emission factors by type can be calculated, as described in previous work (Zhao et al., 2012; Y. Zhao et al., 2013). Therefore the times of implementation of stricter emission standards (e.g., Stage V or VI) in the future are crucial for projecting emission levels in transportation.

Although Stages I–III were implemented roughly at the same time across the country (except for certain megacities like Beijing), the standards under latter stages may come into operation asynchronously by province/region, making the projection quite difficult and uncertain. In BAS, a conservative assumption is made that Stages IV and V for on-road vehicles would take effect from 2013 and 2016 over the entire country, respectively, while those implementation years are expected to move forward to 2011 and 2014 in REF and STD for selected provinces with large and dense vehicle populations, including Tianjin in north-central China, Shanghai, Jiangsu and Zhejiang in eastern China, and Guangdong in south-central China (see Fig. S1 in the Supplement). It should be also noted that certain non-road sources are required as well to gradually meet standards but no differences are assumed between the scenarios of this work. Table S3 in the Supplement summarizes the time schedule of implementation of emission standards for China's transportation sector.

In previous work, the measurements of NO_x and $PM_{2.5}$ emission factors for China's vehicles by type and control stage were thoroughly investigated, and the emission factors used in emission inventory development were derived (Y. Zhao et al., 2013). Those emission factors are applied in BAS and REF scenarios of this work. For STD, an aggressive assumption is made that standard limits would be strictly satisfied, with little effect of vehicle aging on emissions. This is of course an ideal case providing only minimum emissions for a given vehicle population with a fixed fleet composition. Figures 2f–h show the fleet composition and changes in emission factors for typical vehicle types. Faster reduction of NO_x emission factors is expected for light-duty vehicles (as they already have relatively low PM emissions factors) while faster reduction of PM for heavy-duty diesel and rural vehicles.

3.6 Residential and commercial combustion

For the residential and commercial sector, very few measures or standards of emission control have been announced or are expected to be implemented in near future. In most cases, therefore, the emission factors for all of the scenarios are assumed unchanged from 2010, including for coal, oil, gas, and biofuel combustion. One exception is the coal combustion in REF and STD, in which the share of small-coal stoves is assumed to decrease due to penetration of more advanced grate boilers, resulting in reduced PM emission factors.

4 Result and discussion

4.1 Emission trends by scenario

The national emissions in 2015, 2020, and 2030 are summarized by scenario in Table 3, and the emissions in 2010 (Y. Zhao et al., 2013) are provided as well for comparison. The sector distributions of emissions are indicated in Fig. 3 for scenarios with different emission control levels BAS, REF, and STD under a common energy and industrial production trend, the best-guess NPS. Compared to energy and industrial production, the emission control strategies tend to have more effect on the estimated future trends of emissions for all of the concerned pollutants.

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Under the BAS scenarios representing current emission control strategies, national SO_2 emissions are estimated to increase compared to 2010, except for the case of 450S in 2030. Since SO_2 are mainly from fossil fuel combustion, the energy path would have clear impact on future SO_2 trends. Following the conservative CPS path of energy use and industrial production, SO_2 emissions would reach 38.1 Tg in 2030, while it may decrease by 33 % to 25.7 Tg in the aggressive 450S path. With enhanced emission control (REF scenarios), no significant growth of SO_2 emissions are expected after 2010, attributed mainly to the broader use and improved operation of FGD systems. The emissions of the power sector and iron and steel production, for example, are estimated to decrease by 30 % and 41 % respectively from BAS to the REF case under a common NPS energy path in 2030. As a result, the national total SO_2 emissions of REF scenarios are estimated to range 21–24 % lower than those of BAS ones. Should emission standards be fully implemented (STD scenarios), the emissions would be further reduced by 23–26 %. Shown in Fig. 3a, clear changes in sector contributions of emissions exist by year and scenario. Power plants are identified as the biggest contributor in BAS and REF cases, with the shares of emissions increasing slowly from 2015 to 2030. In STD, the shares of the power sector decrease around 20 %, spotlighting the importance of other industrial boilers as significant emission sources that should be of greater concern. A modest reduction of emissions is found for residential and commercial activities, due to the gradually reduced coal consumption for the sector.

The NO_x emission trends in BAS cases would be dominated by fossil fuel use, and the emissions in 2030 are estimated at 38.6, 32.8 and 24.9 Tg (i.e., 134 %, 114 %, and 86 % of emissions in 2010) for CPS, NPS, and 450S cases, respectively. In the REF scenarios, significant benefits would be achieved from the penetration of SCR and LNB technologies in power and industrial sectors. Even with a conservative estimate of national average NO_x-removal efficiencies, the power and cement sectors would see their emissions reduced by 54 % and 48 % respectively from BAS to REF case in 2030 under a common NPS energy path, leading to a 20 % reduction of the national total emissions from 2010 to 2030, from 28.8 to 22.9 Tg. In STD, the very aggressive emission standard for power plants would limit emissions of the sector to 1591 (for 450S) to 3079 Gg (for CPS) in 2030, approximately 80 % lower than the levels in BAS cases. In contrast to power plants, the share of transportation would not significantly decrease for any of the scenarios until 2030, as shown in Fig. 3b. For heavy duty vehicles, the biggest sources of transportation NO_x emissions, current on-road tests failed to find a statistically significant improvement of NO_x emission factors as emission standards became more stringent (Wu et al., 2012). Similar results were also found for rural vehicles (Yao et al., 2011). Stage III and IV vehicles are thus believed to have emission levels close to those of Stages I and II, most likely attributable to similar driving patterns and diesel fuel quality, and NO_x emissions from vehicles are relatively difficult to be reduced in near future.

Coming largely from industrial processes, PM emissions are projected to be less affected by the energy path than SO_2 or NO_x, since the output levels of the main industrial products are estimated to be similar among different energy scenarios. A considerable emission reduction is expected from the further penetration of advanced dust collectors at industrial sources under the national action plan of air pollution control. In the NPS-REF case, as an example, the PM emissions from cement, iron and steel, brick, and non-ferrous metal production in 2030 are estimated to decrease by 74 %, 22 %, 24 %, and 56 % compared to 2010, respectively, leading to a decline of total primary PM emissions from 28.7 to 16.9 Tg during the period. Under implementation of issued or proposed standards (the STD case), PM emissions from brick and non-ferrous metal production in 2030 would be further reduced by 73 % and 52 %, respectively, compared to the REF case. The benefit of emission standards for iron and steel production, however, is limited, since the fugitive dust requirement by the standards, expressed as the ambient dust concentration near the plant, cannot be directly accounted as emission abatement benefit. Regarding PM by size, the shares of finer particles would grow as more stringent control reduces PM overall (chiefly through reduction of coarser particles), raising the difficulty of further reductions because smaller primary particles are more difficult to abate. The mass fractions of $PM_{2.5}$ to total PM, as an example, are estimated to increase from 40 % in BAS cases to 55 % in STD ones for 2030. Shown in Fig. 3c and d, certain industrial sources (e.g., brick and lime production) play important roles in total PM emissions but contribute much less to $PM_{2.5}$. Transportation and residential combustion of fossil fuels and biofuel are thus identified as more important sources of fine particles, particularly as control of industrial emission continues to progress in the future.

4.2 Limitations

In this work, the benefits of national emission control strategies and the most recent emission standards are quantified, although there are still considerable uncertainties. The NO_x emission levels from coal combustion, for example, are influenced by many factors including coal quality, burner types, and combustion operation (Zhao et al., 2010). The actual removal efficiencies of SCR and SNCR systems can vary significantly between individual plants, particularly when those plants are required to reach or even to approach a specific emission standard. It is thus difficult to determine accurate removal efficiencies for the country, even by the power companies themselves (internal communications with director of China Guodian Corporation, one of the largest power companies in China), and the national averages derived from limited tests and expert judgment have to be applied in this work. Similarly, due to a lack of information regarding individual small boilers, the NAPAPPC could not be followed precisely in this work, and local plans for air pollution control are being issued, or will be issued, subsequent to the national one, particularly in provinces with heavy pollution. This leads to divergent emission controls by region in practice. Finally, uniform emission level has to be set in STD for a given type of emission sources due to a lack of detailed individual plant data, resulting in possible overestimates of emissions from plants that actually have lower emission levels than the standards. All of these facts imply a need for further investigation of individual plants in key regions and sectors, to better understand the future trends of China's air pollutant emissions.

Because of the above-mentioned limitations, there are discrepancies between the projected emissions in this work and the national emission targets that are intended to be achieved through full implementation of the emission control strategies, particularly in the near future. For example, the country has announced that the annual emissions of SO_2 and NO_x in 2015 be reduced respectively by 8 % and 10 % compared to those in 2010, while much smaller abatement is found following the NPS-REF path (the "best-guess" case) in this work. To further understand the recent trends of emissions, the vertical column density (VCD) of tropospheric NO_2 from the Ozone Monitoring Instrument (OMI) are used as indirect evidence. The annual NO_2 VCD over mainland China from 2010 to 2013 are calculated and mapped in Fig. S4 in the Supplement based on the monthly data with resolution of $0.125^\circ \times 0.125^\circ$ retrieved by the Royal Netherlands Meteorological Institute (Boersma et al., 2007; http://www.temis.nl/airpollution/no2col/no2regioomimonth_v2.php). Since the data in November and December of 2013 are unavailable at the time of writing, ten-month (from January to October) averages instead of annual means are used for inter-annual comparisons. Although the 10 month mean NO_2 VCD reached a peak in 2011 and started to decline afterwards, the mean VCDs in 2012 and 2013 are still 13 % and 8 % higher than that in 2010, implying incomplete implementation of the emission controls and illustrating the difficulty in national emission reduction. Moreover, as shown in Fig. S4, clear regional discrepancies are found in VCD trends. Compared to megacity areas (e.g., the Yangtze River Delta region), bigger growth in VCDs from 2010 to 2013 are found in less-developed areas, such as north-central and south-central China, consistent with Zhang et al. (2012b). This limited satellite-retrieved VCD data thus reconfirm (1) the importance of careful investigation of emission control implementation to improve the accuracy of emission projections and to ensure the success of national polices, and (2) the necessity of emission trend analysis by region.

4.3 Comparisons with other studies

A series of studies focuses on projections and future trends of China's primary air pollutants. Earlier studies (e.g., Streets and Waldhoff, 2000, and Klimont et al., 2001) were based on relatively conservative projections of energy growth and emission control strategies, and thus are not included in the comparisons of this work. Since 2005, three main groups or research programs have conducted thorough analysis of Chinese future emission trends using different scenarios: the Regional Emission inventory in ASia (REAS, Ohara et al., 2007), the International Institute for Applied System Analysis (IIASA, Amann et al., 2008, and Cofala et al., 2012), and Tsinghua University (Xing et al., 2011, and B. Zhao et al., 2013). Ohara et al. (2007) set three cases to evaluate China's SO_2 and NO_x emissions through 2020: PSC (policy success case), REF (reference case), and PFC (policy failure case). Amann et al. (2008) set CLE (Current Legislation), ACT (Advanced Control Technology) and OPT (a least-cost optimization scenario that would achieve the same health benefit as ACT) cases to analyze the effects of control strategies on the emissions. Cofala et al. (2012) based their study on CPS, NPS, HE (High Energy Efficiency Scenario), and 450S from IEA to analyze the effects of energy path, with few revisions from recent domestic information that is included in this work. Xing et al. (2011) and B. Zhao et al. (2013) devised energy (REF/BAU/PC)-emission control (0/1/2) combination cases to evaluate the possible trends of air pollutants in the future. The results of those studies are compared with this work for SO_2, NO_x, and $PM_{2.5}$ emissions, as shown in Fig. 4a–c, respectively.

Given the discrepancies in energy and emission control assumptions, clear differences exist among these studies for projections of China's future emissions of primary air pollutants. However, this work and other studies share some common judgments: (1) the growth of China's primary air pollutant emission could be constrained through implementation of pollution control strategies committed by the country; and (2) improved control strategies will play a more important role in emission abatement than variations in possible energy paths, as indicated by the larger differences between scenarios in Amann et al. (2008) than those in Cofala et al. (2012). In most cases, the emissions estimated in this work are higher than similar cases from other studies. As shown in Fig. 4b, for example, the NO_x emissions in BAU1 and PC1 of B. Zhao et al. (2013) in 2020 are 28 % and 39 % lower than those in NPS-REF and 450S-REF of this work, respectively, and the analogous values in 2030 would be 31 % and 38 %. The most probable reason for this is that more conservative NO_x removal efficiencies of LNB, SCR, and SNCR are applied in this work, attributed to unclear overall operational conditions of those devices at the national level, as described in Sect. 4.2. There are relatively few studies that include $PM_{2.5}$ because of the higher methodological complexity of its projection than that of other pollutants. Lower emissions are found for this work than Cofala et al. (2012), possibly due to the use of unabated emission factors and removal efficiencies for several dust collector technologies based on recent domestic measurements by the authors (e.g., Zhao et al., 2010).

4.4 Emission control: the imperative to broaden disproportionate focus on coal-fired power, cement, and iron and steel sector

For a long time, China's serious air pollution has been strongly associated with its heavy dependence on coal use for industrial production and electricity generation. Almost half of China's coal is consumed by the coal-fired power sector (CPP), and the coal-fired fraction of total electricity has remained relatively stable at around 80 %. Compiling information at the level of generating units to estimate emissions, the SO_2, NO_x, and PM_{10} emissions from CPP increased by 49 %, 64 %, and 7 % from 2000 to 2005 (Zhao et al., 2008), and CPP accounted for 52 %, 36 %, and 11 % of national emissions of those pollutants in 2005, respectively (Y. Zhao et al., 2013). Given these large shares of air pollutant emissions, CPP has been considered the most important target for emission control across the country since 2005 and great efforts have been made to reduce the emissions from electricity generation. Compulsory requirements in energy conservation and emission control have also been implemented in certain major industrial sources other than CPP, including cement (CEM) and iron and steel production (ISP). To evaluate the effectiveness of the policies targeting large sources, the historical emissions of those sectors and shares of national totals from 2000 to 2012 are analyzed and compared with future trends projected in this work. The historical data come from various sources that follow the same bottom-up emission inventory principles: emissions from CPP are estimated with unit-based information from Zhao et al. (2008); SO_2, NO_x, and PM_{10} emissions from other sources in 2000–2004 are taken respectively from Lu et al. (2011), Zhang et al. (2007) and Lei et al. (2011a); emissions in 2005–2010 are from Y. Zhao et al. (2013); and emissions for 2011 and 2012 are updated following the methodology of Y. Zhao et al. (2013), with the most recent commitment of emission control polices included. For future trends, NPS-REF (the best guess scenario) and NPS-STD (with the best guess of the energy path combined the most aggressive emission control strategies) are selected for comparison.

Shown in Fig. 5 are the annual emissions of SO_2, NO_x and PM_{10} for CPP (Fig. 5a) and CPP + CEM + ISP (Fig. 5b) and their shares of total national emissions of the same pollutants. It is found that the emissions and fractions of SO_2 and PM_{10} for those concerned sources started decreasing around 2005, reflecting the benefits of national pollution control policies set mainly under the 11th Five Year Plan. Even with tightened controls in CPP, CEM, and ISP, however, no further significant reduction of SO_2 and PM_{10} emissions are expected in the NPS-REF scenario, and the fractions to national total emissions are estimated to rise again after 2015, with the lone exception of PM_{10} from CPP + CEM + ISP in 2030. This spotlights the very limited abatement potential remaining in those sectors from a national emission perspective, due to the near saturation of emission control technologies in these industries. For instance, penetration of FGD in the power sector and FF in precalciner cement kilns had reached an estimated 86 % and 83 % of total capacity by 2010, respectively, as discussed earlier. NO_x emissions from these three sectors increased continuously from 2000 to 2012, but the sharply expanded deployment of SCR and SNCR is expected to lead to considerable abatement in these sectors from 2010 to 2015. Similar to SO_2, however, it will become more difficult to reduce NO_x emissions and national fractions from CPP, CEM, and ISP after 2015 because of saturation of these control technologies. It appears clear that a continued disproportionate focus on the major sources of CPP, CEM, and ISP to achieve national goals of air pollution will be inadequate under currently projected trends of energy growth to approach anywhere close to the scale of reductions in SO_2 emissions achieved from 2005 to 2010. If emission standards can be strictly implemented (NPS-STD in Fig. 5), more abatement of emissions could be achieved for these three sectors, but their emissions and fractions would still increase over time despite the aggressive controls. Given the high costs from improved operation of emission control systems to meet the standards, STD is less likely to occur than REF case.

To alleviate China's air pollution effectively in the near future, therefore, it is imperative to broaden the control targets from big sources to other swiftly growing sectors, include building material (brick and lime) production, chemical production, small industrial boilers, and residential stoves. Implementation of energy saving and emission control measures will prove challenging in new ways because of the geographic dispersion of sources in these sectors compared to big sources, and their much greater diversities of production technologies. Thus their emissions will often be much harder to monitor and supervise than those of big sources. In order to restrain national emissions and to prevent deteriorating air quality, however, China has almost no choice but to urgently extend the kind of control measures enacted in CPP, CEM, and ISP to more sectors than ever before. Improved technologies and regulations of energy conservation and emission control, as well as research of those measures, could not be more warranted or timely.

4.5 The trends of PM chemical species and their environmental implications

The future emission trends of PM chemical species, including alkaline dust (calcium (Ca) and magnesium (Mg)) and carbonaceous aerosols (black carbon (BC) and organic carbon (OC)), are projected using the methods and emission factor database provided in our previous work (Zhao et al., 2011; Y. Zhao et al., 2013). It should be noted that the mass fractions of those species for industrial and transportation sectors have to be assumed constant due to a lack of time-series data from measurements. Uncertainty thus may exist in the projection and long-term field tests are suggested to support the time-series analysis of emission factor evolution for those species.

As shown in Table 4, significant abatement of anthropogenic alkaline dust emissions is expected in the REF and STD scenarios. As an example, two thirds of Ca emissions are expected to be cut from 2010 to 2030 in NSP-REF case. Since the alkaline dust is produced most by industrial sources, particularly building material production (cement, lime, and brick), the emissions can be efficiently reduced through the expanded use of advanced dust collectors in those sectors. Fewer benefits are found for carbonaceous aerosols, as the emissions are largely from coal and biofuel combustion in the residential and commercial sector and biomass open burning. In this work, little progress of emission control is assumed for those sources, and the declines of carbonaceous aerosols result mainly from the decreased use of fossil fuel and biomass burning.

The reduced alkaline dust may increase the risks of ecosystem acidification, as the acid-neutralizing capacity would likely decrease as a result. Illustrated in Fig. 6 are the relative changes of China's Ca, PM_{10}, and SO_2 emissions from 2010 to 2030 for two selected scenarios in this work, NPS-REF and NPS-STD. For comparison, the analogous data for the US (USEPA, 2011) and European Union (CEIP, 2011) are shown as well from 1990 to 2010, the 20 years following enactment of the 1990 amendments to the US Clean Air Act (only SO_2 and PM_{10} were reported; no Ca data are available). In contrast to the greater reductions of SO_2 than PM historically in the US and EU, a much faster decrease in Ca emissions than SO_2 is projected for China in the future, implying that recovery of acidification in the country will be a considerable challenge under the current national emission control commitment. Long-term observations at different sites across China have partly confirmed the increased acidity of precipitation and decreased alkaline species within in, particularly in rural areas (Tang et al., 2010; Wang et al., 2012). As the serious haze and PM pollution is now becoming the biggest focus of air quality improvement, the continuous abatement of primary PM (and thereby alkaline base cations) would gradually lead to clearer skies in urban areas but may exacerbate regional acid deposition, particularly if the potential for continued SO_2 reduction grows more constrained in the future.

Besides local and regional conventional air pollution impacts, the future trends of aerosols can affect regional climate as well. In this work the changes of radiative forcing (RF) from trends in China's short-lived species are evaluated as the sum of emission-based constituent global forcing (CGF) of SO_2, NO_x, BC, and OC, weighted by the changes in China's emissions as percentages of total global emissions, following the methods of Carmichael et al. (2002). The emission-based CGF represents that emissions of a single primary precursor can affect several related forcing agents, and the values are taken from Carmichael et al. (2002) and IPCC (2007). It should be acknowledged that the forcing efficacy from those short-lived species is assumed constant for a rough estimate. For China's future emissions from 2010 to 2030, five scenarios are selected for analysis: besides the best guess of NPS-REF, CPS-REF and 450-REF are used to evaluate the effects of energy paths, and NPS-BAS and NPS-STD for those of emission control strategies. The global emissions of SO_2 and NO_x in CPS, NPS, and 450S are obtained from Cofala et al. (2012), while those of carbonaceous aerosols are from Klimont et al. (2014) that applies the same methodology as Klimont et al. (2009) and Bond et al. (2013). Emissions from global biomass open burning are taken from Bond et al. (2004).

As shown in Fig. 7, the reduced primary carbonaceous emissions played similar roles in RF change from CPS-REF to 450S-REF, as the fossil fuel energy path (driven by industrial and power generation demand) have limited effects on BC and OC emissions. The warming effects of SO_2 reduction are expected to increase, as the emissions would be reduced resulting from reduced coal combustion. Under a common energy path (NPS), both the cooling effects from BC reduction and warming effects from SO_2 reduction are expected to grow with improved implementation of emission control. The SO_2 reduction would dominate the RF changes, because current emission control commitments and standards focus little on the residential coal and biofuel combustion that generates most of the carbonaceous aerosols. The tightened controls in China are thus expected to result in enhanced RF in the future. The expanded attention and efforts on the scattered residential sources such as small coal and biofuel stoves would not only lead to improved local and regional air quality, but also help limit regional warming from short-lived climate forcing.

5 Conclusions

Given the high frequency of serious haze and heavy urban and regional air pollution events, China has announced a national action plan of air pollution control, and a series of measures in energy conservation and emission reduction will be implemented in the coming years. The effectiveness and benefits of those measures on future national emission abatement are evaluated in this work using scenarios coupling different levels of energy consumption with several emission control strategies. Should current policy commitments be implemented, China's primary pollutant emissions are expected to be restrained in the future, including emissions of NO_x that have grown almost continuously in recent years. However, compromised operational conditions of swiftly disseminating air pollutant control devices (e.g., SCR systems) may partly undermine the benefits of emission abatement in the near future, as suggested by satellite-retrieved NO_2 vertical column densities observed across the country. Compared to the energy path, the levels of emission control implementation will play more important roles in future trends of emissions for all of the concerned pollutants, particularly for primary aerosols that depend largely on non-combustion industrial processes. Should the emission standards across sectors that have been either issued or proposed be fully met, they could prove highly effective at emission abatement.

Limitations exist for current policy commitments and emission standards. Because of high penetration of emission control devices in key sectors in recent years, the potential for further emission reductions from those sources may be limited despite aggressive control efforts. Therefore, greater efforts should be made to target the small coal and biofuel combustion stoves that generate much more fine particles and carbonaceous aerosols than large, energy-efficient boilers, resulting in benefits both to air quality and regional climate. As it is becoming more and more difficult to further reduce SO_2, the swift declines in alkaline dust emissions in the future would likely increase acidification risks to ecosystems, as indicated by long-term observations at a number of sites. Thus not only the total amounts of emissions but also the linkages between emissions and various environmental impacts need to be comprehensively considered in policy making. Finally, the highly imbalanced economic development and urbanization by region in China are currently leading to major discrepancies in atmospheric pollution and control strategies across the country. Limits of data preclude better understanding of regional differentiation of future technology innovation, emission control plans, and thereby emission trends. Further investigations of emission source changes and spatial distributions are thus urgently needed to reduce uncertainties in analysis of future emission trends and related impacts, and to better support air pollution control planning across the country.

Supplementary material related to this article is available online at http://www.atmos-chem-phys-discuss.net/14/7917/2014/acpd-14-7917-2014-supplement.pdf.

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References

Anshan Iron and Steel Group Corporation (AISGC): The explanation for emission standard of air pollutants for iron and steel industry-sintering, Internal Report, Beijing, China, 2007 (in Chinese).

Amann, M., Jiang, K. J., Hao, J. M., and Wang, S. X.: Scenarios for cost-effective control of air pollution and greenhouse gases in China, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2008.

Baosteel Group Corporation (BGC): The explanation for emission standard of air pollutants for iron and steel industry-steel smelting, Internal Report, Beijing, China, 2007 (in Chinese).

Boersma, K. F., Eskes, H. J., Veefkind, J. P., Brinksma, E. J., van der A, R. J., Sneep, M., van den Oord, G. H. J., Levelt, P. F., Stammes, P., Gleason, J. F., and Bucsela, E. J.: Near-real time retrieval of tropospheric NO_2 from OMI, Atmos. Chem. Phys., 7, 2103–2118, doi:10.5194/acp-7-2103-2007, 2007.

Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J.-H., and Klimont, Z.: A technology-based global inventory of black and organic carbon emissions from combustion. J. Geophys. Res., 109, D14203, doi:10.1029/2003JD003697, 2004.

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., and Zender, C. S.: Bounding the role of black carbon in the climate system: a scientific assessment, J. Geophys. Res., 118, 5380–5552, 2013.

Carmichael, G. R., Streets, D. G., Calori, G., Amann, M., Jacobson, M. Z., Hansen, J., and Ueda, H.: Changing trends in sulfur emissions in Asia: implications for acid deposition, air pollution, and climate, Environ. Sci. Technol., 36, 4707–4713, 2002.

Centre on Emission Inventories and Projections (CEIP): Officially reported emission data, available at: http://www.ceip.at/webdab-emission-database/officially-reported-emission-data/ (last access: 20 March 2014), 2011.

Chinese Research Academy of Environmental Sciences (CRAES): The explanation for emission standard of pollutants for copper, nickel, cobalt industry (in Chinese), available at:

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http://www.mep.gov.cn/gkml/zj/bgth/200910/W020071128478677308568.pdf (last access: 20 March 2014), 2007.

Chinese Research Academy of Environmental Sciences (CRAES): The explanation for emission standard of air pollutants for brick industry (in Chinese), available at: http://www.zhb.gov.cn/gkml/hbb/bgth/200912/W020091202540222872323.pdf (last access: 20 March 2014), 2009.

Cofala, J., Bertok, I., Borken-Kleefeld, J., Heyes, C., Klimont, Z., Rafaj, P., Sander, R., and Schopp, W.: Emissions of Air Pollutants for the World Energy Outlook 2012 Energy Scenarios 2012, Draft Final Report, Contract No. 12–129, International Institute for Applied System Analysis, Laxenburg, Austria, 2012.

He, Q. S.: Composite characteristics, emission factors, and emission estimates of particulates and volatile organic compound from coke making in China, Doctoral Thesis, Chinese Academy of Sciences, Beijing, China, 2006.

Huo, H., Wang, M., Zhang, X. L., He, K. B., Gong, H. M., Jiang, K. J., Jin, Y. F., Shi, Y. D., and Yu, X.: Projection of energy use and greenhouse gas emissions by motor vehicles in China: policy options and impacts, Energ. Policy, 43, 37–48, 2012a.

Huo, H., Lei, Y., Zhang, Q., Zhao, L. J., and He, K. B.: China's coke industry: recent policies, technology shift, and implication for energy and the environment, Energ. Policy, 51, 397–404, 2012b.

International Energy Agency (IEA): World Energy Outlook 2012, International Energy Agency, Paris, France, 2012.

Intergovernmental Panel on Climate Change (IPCC): Climate change 2007 – the physical science basis, Contribution of working group I to the fourth assessment report of the IPCC, New York, USA, 2007.

Kan, H. D., Chen, R. J., Tong, S. L.: Ambient air pollution, climate change, and population health in China, Environ. Int., 42, 10–19, 2012.

Klimont, Z., Cofala, J., Schopp, W., Amann, M., Streets, D. G., Ichikawa, Y., and Fujita, S.: Projections of SO_2, NO_x, NH_3 and VOC emissions in East Asia up to 2030, Water Air Soil Poll., 130, 193–198, 2001.

Klimont, Z., Cofala, J., Xing, J., Wei, W., Zhang, C. Y., Wang, S. X., Jiang, K. J., Bhandari, P., Mathur, R., Purohit, P., Rafaj, P., Chambers, A., and Amann, M: Projections of SO_2, NO_x, and carbonaceous aerosols emissions in Asia, Tellus B, 61, 602–617, 2009.

Klimont, Z., Kupiainen, K., Heyes, Ch., Purohit, P., Cofala, J., Rafaj, P., and Schopp, W.: Global anthropogenic emissions of particulate matter, in preparation, 2014.

Larssen, T., Lydersen, E., Tang, D. G., He, Y., Gao, J. X., Liu, H. Y., Duan, L., Seip, H. M., Vogt, R. D., Mulder, J., Shao, M., Wang, Y. H., Shang, H., Zhang, X. S., Solberg, S., Aas, W., Okland, T., Eilertsen, O., Angell, V., Liu, Q. R., Zhao, D. W., Xiang, R. J., Xiao, J. S., and Luo, J. H.: Acid rain in China, Environ. Sci. Technol., 40, 418–425, 2006.

Lei, Y., Zhang, Q., He, K. B., and Streets, D. G.: Primary anthropogenic aerosol emission trends for China, 1990–2005, Atmos. Chem. Phys., 11, 931–954, doi:10.5194/acp-11-931-2011, 2011a.

Lei, Y., Zhang, Q., Nielsen, C. P., and He, K. B.: An inventory of primary air pollutants and CO_2 emissions from cement industry in China, 1990–2020, Atmos. Environ., 45, 147–154, 2011b.

Li, C., Zhang, Q., Krotkov, N. A., Streets, D. G., He, K. B., Tsay, S. C., and Gleason, J. F.: Recent large reduction in sulfur dioxide emissions from Chinese power plants observed by the Ozone Monitoring Instrument, Geophys. Res. Lett., 37, L08807, doi:10.1029/2010GL042594, 2010.

Li, D. L.: Study on emission inventory of non-road mobile sources in China, Master Thesis, Tsinghua University, Beijing, China, 2011.

Lin, J. T., Nielsen, C. P., Zhao, Y., Lei, Y., Liu, Y., and McElroy, M. B.: Recent changes in particulate air pollution over China observed from space and the ground: effectiveness of emission control, Environ. Sci. Technol., 44, 7771–7776, 2010.

Lu, Z., Streets, D. G., Zhang, Q., Wang, S., Carmichael, G. R., Cheng, Y. F., Wei, C., Chin, M., Diehl, T., and Tan, Q.: Sulfur dioxide emissions in China and sulfur trends in East Asia since 2000, Atmos. Chem. Phys., 10, 6311–6331, doi:10.5194/acp-10-6311-2010, 2010.

Lu, Z., Zhang, Q., and Streets, D. G.: Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996–2010, Atmos. Chem. Phys., 11, 9839–9864, doi:10.5194/acp-11-9839-2011, 2011.

Ma, J. Z., Xu, X. B., Zhao, C. S., and Yan, P.: A review of atmospheric chemistry research in China: photochemical smog, haze pollution, and gas-aerosol interactions, Adv. Atmos. Sci., 29, 1006–1026, 2012.

Matus, K., Nam, K. M., Selin, N. E., Lamsal, L. N., Reilly, J. M., and Paltsev, S.: Health damages from air pollution in China, Global Environ. Chang., 22, 55–66, 2012.

Ministry of Environmental Protection in China (MEP): The handbook of emission factors of industrial sources for the first national survey on pollutant sources, Beijing, China, 2010 (in Chinese).

Ministry of Industry and Information Technology (MIIT): The direction of technology improvement and investment for automobile industry, available at: http://www.miit.gov.cn/n11293472/n11293832/n12843956/n13227851.files/n13226869.xls (last access: 20 March 2014), 2010.

Ohara, T., Akimoto, H., Kurokawa, J., Horii, N., Yamaji, K., Yan, X., and Hayasaka, T.: An Asian emission inventory of anthropogenic emission sources for the period 1980–2020, Atmos. Chem. Phys., 7, 4419–4444, doi:10.5194/acp-7-4419-2007, 2007.

Ou, X., Zhang, X., and Chang, S.: Scenario analysis on alternative fuel/vehicle for China's future road transport: life-cycle energy demand and GHG emissions, Energ. Policy, 38, 3943–3956, 2010.

Parrish, D. D. and Zhu, T.: Clean air for megacities, Science, 326, 674–675, 2009.

Richter, A., Burrows, J. P., Nuss, H., Granier, C., and Niemeier, U.: Increase in tropospheric nitrogen dioxide over China observed from space, Nature, 437, 129–132, 2005.

Sinosteel Corporation (SSC): The explanation for emission standard of air pollutants for iron and steel industry-iron making, Internal Report, Beijing, China, 2007 (in Chinese).

Streets, D. G. and Waldhoff, S. T.: Present and future emissions of air pollutants in China: SO_2, NO_x, and CO, Atmos. Environ., 34, 363–374, 2000.

Tang, J., Xu, X. B., Ba, J., and Wang, S. F.: Trends of the precipitation acidity over China during 1992–2006, Chinese. Sci. Bull., 55, 1800–1807, 2010.

US Environmental Protection Agency (USEPA): Emission inventory information, available at: http://www.epa.gov/ttn/chief/trends/index.html (last access: 20 March 2014), 2011.

van Donkelaar, A., Martin, R. V., Brauer, M., Kahn, R., Levy, R., Verduzco, C., and Villeneuve, P. J.: Global estimates of ambient fine particulate matter concentrations from satellite-based aerosol optical depth: development and application, Environ. Health Persp., 118, 847–855, 2010.

Wang, F.: The control policy for total emission amount of primary pollutants during the 12th Five Year Plan period, presented at the 17th Workshop on SO_2, NO_x, and Hg pollution control technology and $PM_{2.5}$ control and monitoring technology, Hangzhou, China, 16–17 May, 2013.

Wang, L. T., Wei, Z., Yang, J., Zhang, Y., Zhang, F. F., Su, J., Meng, C. C., and Zhang, Q.: The 2013 severe haze over the southern Hebei, China: model evaluation, source apportionment, and policy implications, Atmos. Chem. Phys. Discuss., 13, 28395–28451, doi:10.5194/acpd-13-28395-2013, 2013.

Wang, M., Huo, H., Johnson, L., and He, D.: Projection of Chinese motor vehicle growth, oil demand, and CO_2 emissions through 2050, Argonne National Laboratory, ANL/ESD/06–6, Illinois, USA, 2006.

Wang, S. X. and Hao, J. M.: Air quality management in China: issues, challenges, and options, J. Environ. Sci., 24, 2–13, 2012.

Wang, S. X., Zhao, M., Xing, J., Wu, Y., Zhou, Y., Lei, Y., He, K. B., Fu, L. X., and Hao, J. M.: Quantifying the air pollutants emission reduction during the 2008 Olympic Games in Beijing, Environ. Sci. Technol., 44, 2490–2496, 2010.

Wang, Y., Hao, J., McElroy, M. B., Munger, J. W., Ma, H., Chen, D., and Nielsen, C. P.: Ozone air quality during the 2008 Beijing Olympics: effectiveness of emission restrictions, Atmos. Chem. Phys., 9, 5237–5251, doi:10.5194/acp-9-5237-2009, 2009.

Wang, Y. S., Yu, W. P., Pan, Y. P., and Wu, D.: Acid neutralization of precipitation in Northern China, J. Air Waste Manage., 62, 204–211, 2012.

Wang, Y. S., Yao, L., Wang, L. L., Liu, Z. R., Ji, D. S., Tang, G. Q., Zhang, J. K., Sun, Y., Hu, B., and Xin, J. Y.: Mechanism for the formation of the January 2013 heavy haze pollution episode over central and eastern China, Sci. China Ser. D, 57, 14–25, 2014.

World Bank (WB) and State Environmental Protection Administration (SEPA): Cost of pollution in China, Rural Development, Natural Resources and Environment Management Unit, East Asia and Pacific Region, The World Bank, Washington DC, available at: http://www.worldbank.org/eapenvironment (last access: 20 March 2014), 2007.

Wu, Y., Zhang, S. J., Li, M. L., Ge, Y. S., Shu, J. W., Zhou, Y., Xu, Y. Y., Hu, J. N., Liu, H., Fu, L. X., He, K. B., and Hao, J. M.: The challenge to NO_x emission control for heavy-duty diesel vehicles in China, Atmos. Chem. Phys., 12, 9365–9379, doi:10.5194/acp-12-9365-2012, 2012.

Xing, J., Wang, S. X., Chatani, S., Zhang, C. Y., Wei, W., Hao, J. M., Klimont, Z., Cofala, J., and Amann, M.: Projections of air pollutant emissions and its impacts on regional air quality in China in 2020, Atmos. Chem. Phys., 11, 3119–3136, doi:10.5194/acp-11-3119-2011, 2011.

Xu, M. and Wang, Y. J.: The potential and countermove of energy-saving and cutting pollution about brick and tile industry in China, Brick and Tile World, 7, 6–11, 2007 (in Chinese).

Yao, Z. L., Huo, H., Zhang, Q., Streets, D. G., and He, K. B.: Gaseous and particulate emissions from rural vehicles in China, Atmos. Environ., 45, 3055–3061, 2011.

Zhang, Q., He, K. B., and Huo, H.: Cleaning China's air, Nature, 484, 161–162, 2012a.

Zhang, Q., Geng, G. N., Wang, S. W., Richter, A., and He, K. B.: Satellite remote sensing of changes in NO_x emissions over China during 1996–2010, Chinese Sci. Bull., 57, 2857–2864, doi:10.1007/s11434-012-5015-4, 2012b.

Zhang, Q., Streets, D. G., He, K. B., Wang, Y. X., Richter, A., Burrows, J. P., Uno, I., Jang, C. J., Chen, D., Yao, Z. L., and Lei, Y.: NO_x emission trends for China, 1995–2004: the view from the ground and the view from space, J. Geophys. Res., 112, D22306, doi:10.1029/2007JD008684, 2007.

Zhao, B., Wang, S. X., Liu, H., Xu, J. Y., Fu, K., Klimont, Z., Hao, J. M., He, K. B., Cofala, J., and Amann, M.: NO_x emissions in China: historical trends and future perspectives, Atmos. Chem. Phys., 13, 9869–9897, doi:10.5194/acp-13-9869-2013, 2013.

Zhao, Y., Wang, S. X., Duan, L., Lei, Y., Cao, P. F., and Hao, J. M.: Primary air pollutant emissions of coal-fired power plants in China: current status and future prediction, Atmos. Environ., 42, 8442–8452, 2008.

Zhao, Y., Duan, L., Xing, J., Larssen, T., Nielsen, C. P., and Hao, J. M.: Soil acidification in China: is controlling SO_2 emissions enough, Environ. Sci. Technol., 43, 8021–8026, 2009.

Zhao, Y., Wang, S. X., Nielsen, C. P., Li, X. H., and Hao, J. M.: Establishment of a database of emission factors for atmospheric pollutants from Chinese coal-fired power plants, Atmos. Environ., 44, 1515–1523, 2010.

Zhao, Y., Duan, L., Lei, Y., Xing, J., Nielsen, C. P., and Hao, J. M.: Will PM control undermine China's efforts to reduce soil acidification, Environ. Pollut., 159, 2726–2732, 2011a.

Zhao, Y., Nielsen, C. P., Lei, Y., McElroy, M. B., and Hao, J.: Quantifying the uncertainties of a bottom-up emission inventory of anthropogenic atmospheric pollutants in China, Atmos. Chem. Phys., 11, 2295–2308, doi:10.5194/acp-11-2295-2011, 2011b.

Zhao, Y., Nielsen, C. P., McElroy, M. B., Zhang, L., and Zhang, J.: CO emissions in China: uncertainties and implications of improved energy efficiency and emission control, Atmos. Environ., 49, 103–113, 2012.

Zhao, Y., Zhang, J., and Nielsen, C. P.: The effects of recent control policies on trends in emissions of anthropogenic atmospheric pollutants and CO_2 in China, Atmos. Chem. Phys., 13, 487–508, doi:10.5194/acp-13-487-2013, 2013.

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Table 1. The basic principles and assumptions of energy path and emission control strategies for scenarios in this work.

Scenarios	Descriptions
Energy and industrial production path	
CPS	Current Policy Scenario (following IEA): conservative estimates with assumption that national energy policy will not change since 2010; modification on power and transportation sector based on most recent domestic plans or research
NPS	New Policy Scenario (following IEA): "best guess" of future energy trend including the national energy policy commitments that have been announced; modification on power and transportation sector based on most recent domestic plans or research
450S	450 Scenario (following IEA): the most aggressive scenario in terms of energy conservation and greenhouse emission reduction; modification on power and transportation sector based on most recent domestic plans or research
Emission control strategies	
BAS	Base Case: conservative case that assumes unchanged emission control levels from 2010
REF	Reference Case: "best guess" case including new improvements of emission control according to the national plan of air pollution control action
STD	Fully Implemented Emission Standard Case: aggressive case that assumes the recently issued emission standards with strict limits are satisfied by all the sources

Table 2. The capacity and coal consumption of China's coal-fired power plants predicted by IEA and this work.

		Capacity (GW)				Coal consumption (MMT)			
		IEA Total	This work			IEA Total	This work		
			Old units	New units	Total		Old units	New units	Total
2015	CPS	–	588	406	993	–	1265	862	2127
	NPS	885	588	402	989	2244	1265	854	2119
	450S	–	588	350	938	–	1265	745	2010
2020	CPS	1080	579	597	1176	2644	1246	1269	2514
	NPS	982	579	469	1048	2350	1246	997	2242
	450S	859	579	420	1000	1938	1246	893	2139
2030	CPS	1358	555	897	1452	3254	1179	1906	3085
	NPS	1079	555	591	1146	2478	1179	1256	2435
	450S	668	555	119	674	1398	1179	252	1431

Table 3. Projected national emissions of anthropogenic SO_2, NO_x, and PM for 2015, 2020 and 2030 by scenario (Unit: Gg). The emissions of 2010 (Y. Zhao et al., 2013) are listed as well for comparison.

		2010	2015			2020			2030		
			BAS	REF	STD	BAS	REF	STD	BAS	REF	STD
SO_2	CPS	27 714	33 838	27 046	20 172	36 302	28 118	20 683	38 097	28 917	21 258
	NPS		33 360	26 792	19 935	34 365	26 885	19 954	33 108	25 676	19 202
	450S		32 412	26 234	19 579	33 414	26 316	19 577	25 678	20 213	15 516
NO_x	CPS	28 816	35 939	28 221	20 061	38 560	28 726	20 646	38 573	26 225	19 280
	NPS		35 125	27 511	19 613	35 533	26 699	19 323	32 803	22 933	17 361
	450S		33 215	26 074	18 827	34 437	26 010	18 883	24 899	18 597	14 838
PM	CPS	28 746	29 952	26 911	21 261	30 970	26 025	20 812	27 615	17 793	14 373
	NPS		29 724	26 699	21 060	30 561	25 673	20 505	26 575	16 854	13 607
	450S		29 469	26 472	20 856	30 319	25 460	20 306	25 168	15 630	12 523
PM_{10}	CPS	16 990	17 241	15 746	12 926	17 488	15 144	12 518	15 628	11 789	10 251
	NPS		17 087	15 599	12 789	17 178	14 876	12 296	14 890	11 129	9739
	450S		16 896	15 426	12 641	17 005	14 721	12 157	13 860	10 233	8985
$PM_{2.5}$	CPS	12 212	12 431	11 525	9537	12 479	11 104	9201	11 219	8853	7751
	NPS		12 318	11 419	9440	12 251	10 905	9045	10 713	8402	7426
	450S		12 174	11 288	9333	12 128	10 795	8949	10 004	7791	6942

Table 4. Projected national emissions of chemical species of PM (Ca, Mg, BC, and OC) for 2015, 2020 and 2030 by scenario (Unit: Gg). The emissions of 2010 (Y. Zhao et al., 2013) are listed as well for comparison.

		2010	2015			2020			2030		
			BAS	REF	STD	BAS	REF	STD	BAS	REF	STD
Ca	CPS	4253	4569	3951	3648	4719	3747	3514	3901	1461	1325
	NPS		4462	3941	3638	4699	3729	3499	3844	1412	1286
	450S		4453	3933	3630	4688	3720	3490	3782	1359	1240
Mg	CPS	356	394	360	275	390	363	276	359	249	201
	NPS		369	358	273	385	359	272	346	236	191
	450S		367	356	271	383	357	270	331	222	180
BC	CPS	1667	1717	1627	1341	1658	1534	1260	1505	1282	1117
	NPS		1688	1599	1316	1616	1495	1225	1429	1199	1058
	450S		1650	1562	1285	1599	1479	1209	1352	1123	991
OC	CPS	2848	2885	2729	2460	2782	2580	2325	2423	2037	1891
	NPS		2853	2699	2433	2745	2547	2294	2346	1968	1841
	450S		2829	2677	2415	2726	2530	2277	2262	1894	1774

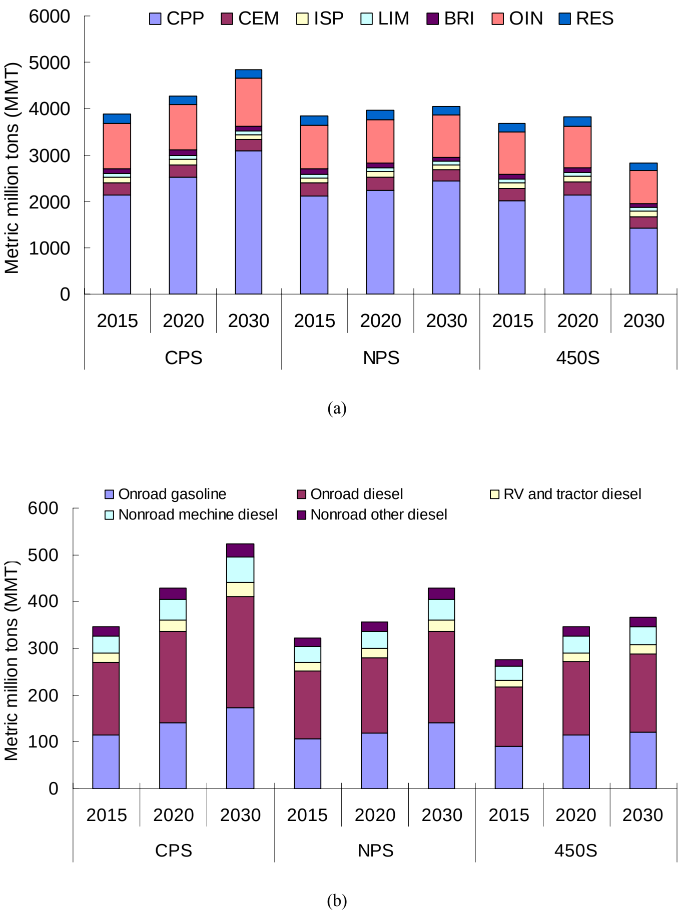
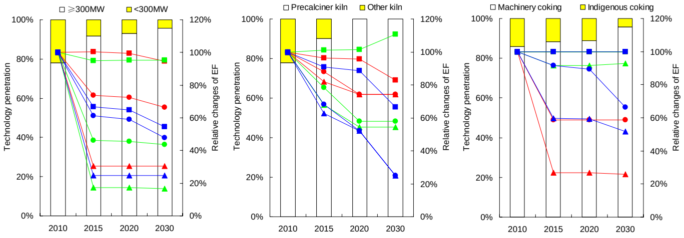
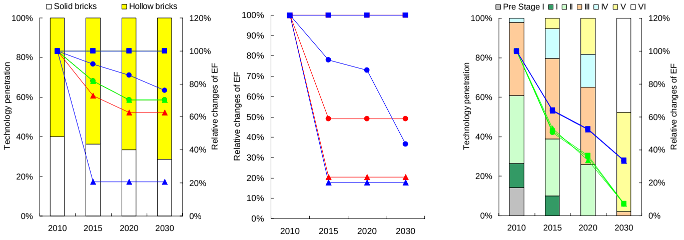


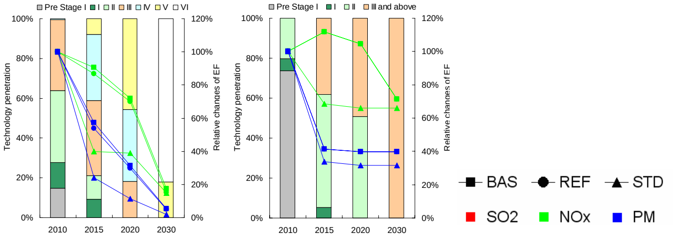
Fig. 1. The projection of China's energy use for 2015, 2020 and 2030. **(a)** Coal consumption by sector and scenario; and **(b)** Oil consumption of transportation by vehicle type and scenario.



(a) Coal-fired power plants (b) Cement production (c) Iron & steel production



(d) Brick production (e) Nonferrous metallurgy (f) Light-duty gasoline vehicles



(g) Heavy-duty diesel vehicles (h) Rural vehicles

Fig. 2. The projected trends in penetrations of technologies and emission factors for typical sources in China from 2010 to 2030. All of the panels are for NPS. (Similar trends are projected for CPS and 450S, and are thus not shown here for paper length.) In each panel, the penetrations of various technologies for REF are indicated on the left-hand vertical axis and the emission factors relative to 2010 levels for BAS, REF, and STD on the right-hand vertical axis (except for nonferrous metal production).

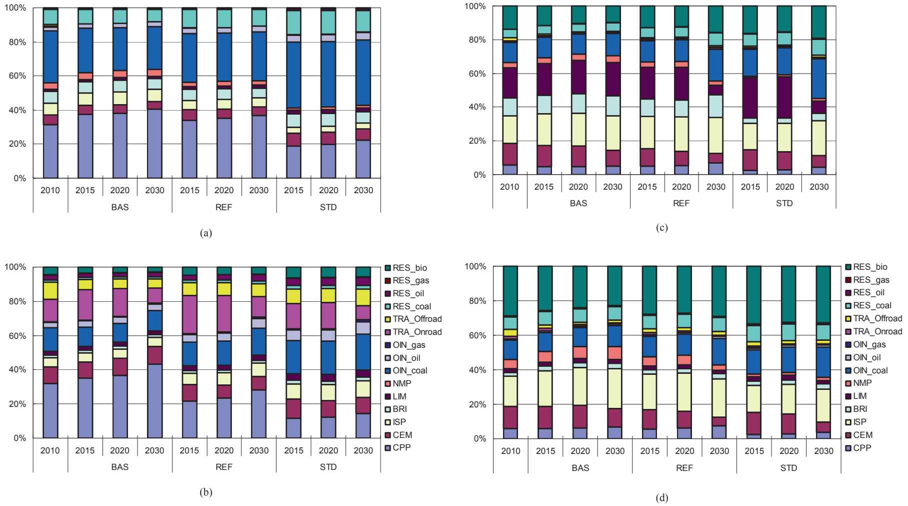


Fig. 3. The shares of China's anthropogenic emissions by source for 2015, 2020 and 2030. All the panels are for NPS scenarios (i.e., different emission control levels BAS, REF and STD with common NPS energy trend). **(a)** SO$_2$; **(b)** NO$_x$; **(c)** PM; and **(d)** PM$_{2.5}$.

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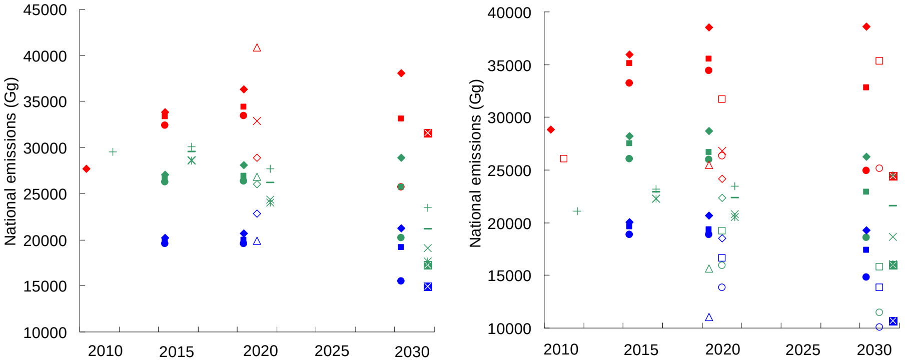
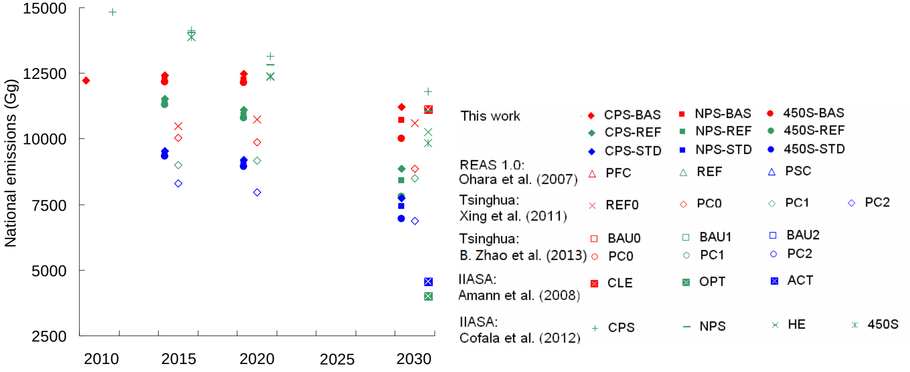


(a) SO_2 (b) NO_X



(c) $PM_{2.5}$

Fig. 4. Comparisons of projected Chinese emissions between this work and other studies. **(a)** SO_2; **(b)** NO_x and **(c)** $PM_{2.5}$.

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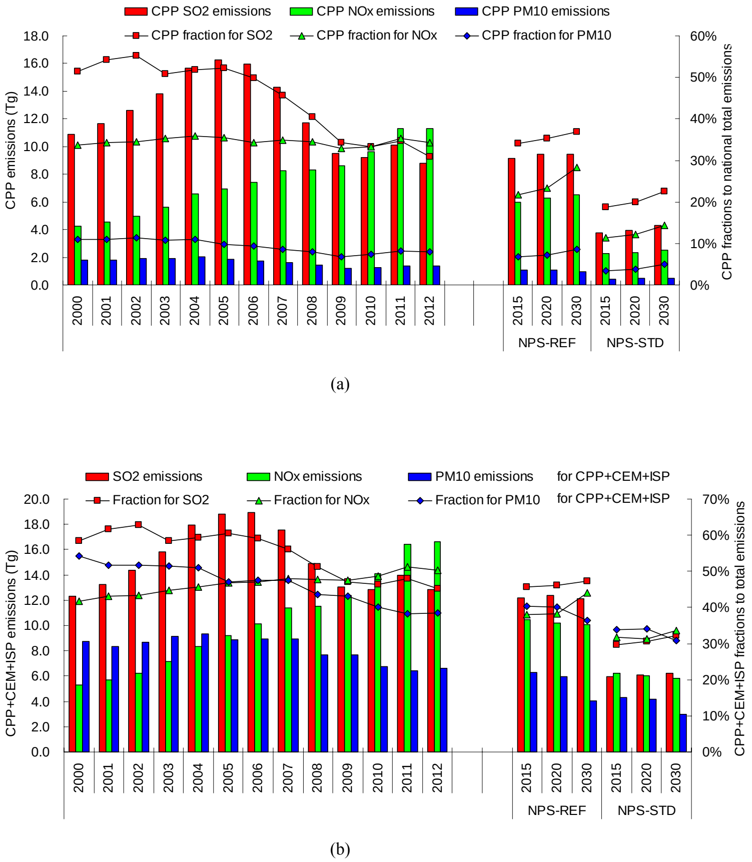

Fig. 5. China's annual emissions (left scale) and fractions of total national emissions (right scale) of given sources (**(a)**: CPP; and **(b)**: CPP + CEM + ISP) for 2000–2012 and the projected values for 2015, 2020 and 2030 under NPS-REF and NPS-STD scenarios.

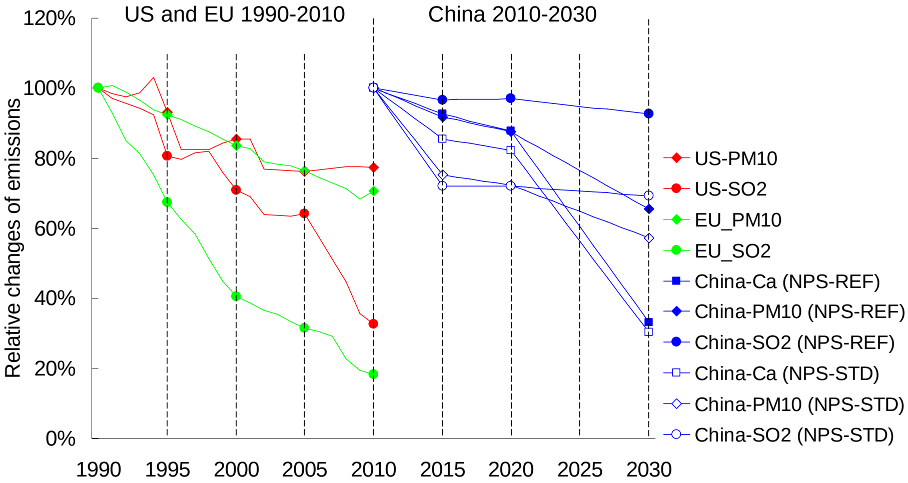

Fig. 6. Relative changes of PM_{10} and SO_2 emissions for US (red) and EU (green) in 1990–2010 and those of PM_{10}, Ca, and SO_2 for China in 2010–2030 under NPS-REF (solid blue) and NPS-STD (hollow blue) scenarios in this work.

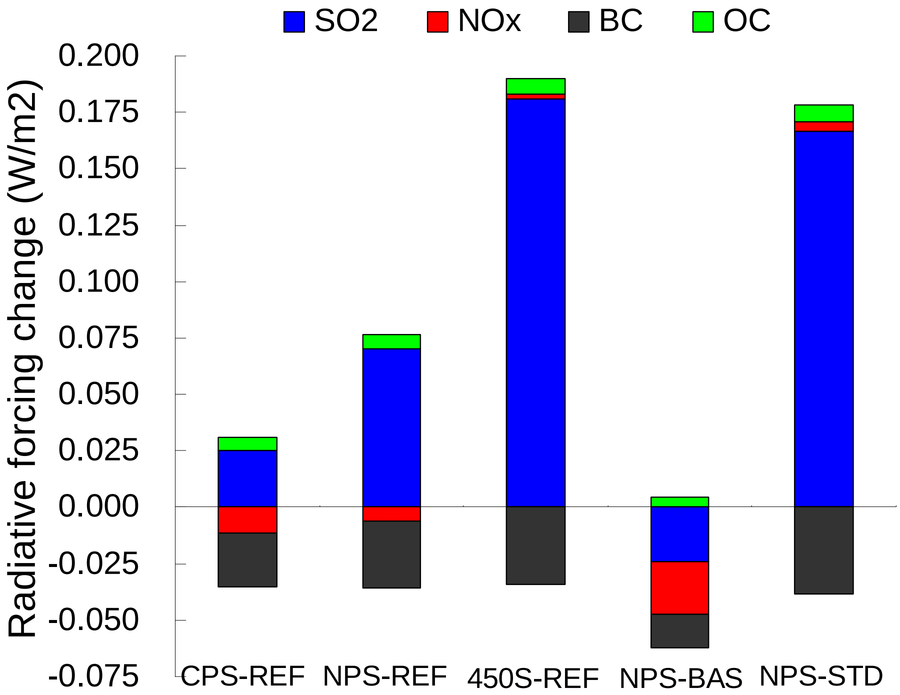

Fig. 7. The effects of future trends of China's air pollutant emissions from 2005 to 2030 on radiative forcing for selected scenarios in this work.