

Anonymous Referee #1

On the basis of the CPED database, including the detailed information of over 7600 individual coal-fired power plants and supplements with aggregated data, the authors developed a comprehensive and high resolution emission inventory for SO₂, NO_x, PM_{2.5} and CO₂ from China's coal-fired power plants during the period 1990 to 2010. Undoubtedly, emission inventories for SO₂, NO_x, PM_{2.5} and CO₂ in this study, which are characterized by higher spatial resolution and more accurate temporal profile due to the extensive use of unit-based data, are necessary data for improvement the performances of regional air quality modelling by using chemical transport models (e.g., WRF-CMAQ, WRF-CHEM, etc.) and policymaking for their emission control. In general, the present manuscript is well written and presented with good quality, and I recommend the publication acceptance of the manuscript. However, some minor revision comments and suggestions should be addressed before the manuscript can be accepted for final publication.

Response: We thank Referee #1 for the encouraging comments. All comments and suggestions have been considered carefully and well addressed.

Specific comments:

(1) Compared to previous emission inventories, the values of emissions from China's coal-fired power plants estimated by authors are deemed to be much higher reliability on accounting of extensive use of underlying data at unit level. Nevertheless, the detailed activity data using in equation 1, 2 and 3 obtained from MEP-database is unpublished data. Therefore, in order to further convince the international readers of ACP, I recommend the authors supply some much more detailed information about parameters using in the emission calculation, especially for the data in 2010, such as provincial data of P, H, SCC, AC, etc.

Response: The provincial data of P, H, SCC and AC for the year 2010 are provided in Table S3 of the supplemental information. We also added a sentence to indicate the availability of the data in the Sect. 2.2 of the revised manuscript.

(2) With the replacement of small plants with large and high-efficiency units and the continuously increasing application rate of advanced technologies, dynamic emission factors are applied in this study to estimate the historical emission inventory for SO₂, NO_x, PM_{2.5} and CO₂ during 1990-2010. The authors are recommended to make the verification for historical emissions by using of valid index, such as ground-level or satellite based ambient concentrations of above pollutants in China.

Response: Validation against to ground-level or satellite based observations provides a good way of evaluating emission inventories. Developing the relationship between power plant emissions and observations is a challenging task given that observations also contain information of other emitting sources. We believe this is beyond of the scope of this paper. In another paper (Liu et al., 2015), we developed a new approach to quantify NO_x emissions from OMI NO₂ observations for non-isolated sources, which addressed the questions raised by the referee. In the revised manuscript, we have added the citation to Liu et al. (2015) to support the validation of the CPED

Anonymous Referee #3

This paper estimated emissions from China's coal-fired power plants at unit level for a 20 year period. Compared to previous emission inventories, CPED significantly improved the spatial resolution and temporal profile of power plant emission inventory in China. The new inventory developed in this study will enable a close examination for temporal and spatial variations of power plant emissions in China and will help to improve the performances of chemical transport models by providing more accurate emission data. The paper is well structured and written. I would recommend publishing this paper after addressing some general comments and minor revisions. Before publication, making the emission inventory open to public is highly encouraged (or required?).

Response: We thank Referee #2 for the encouraging comments. All specific comments have been addressed below. Particularly, CPED has been integrated into the MEIC (Multi-resolution Emission Inventory for China) database, which is available at the following website: <http://www.meicmodel.org/>. In the Sect. 3.6 of the revised manuscript, we added a paragraph to clarify the availability of CPED.

General comments:

(1) Besides SO₂, NO_x, CO₂, PM_{2.5}, did the authors also estimate CO, VOC, PM_{coarse}, BC, OC from coal-fired power plants? Do the authors plan other papers to report other compounds? Why did the authors select the four compounds as in the paper? Please say more.

Response: We didn't provide CO, VOC, BC and OC emission estimates in this work because emissions of these species are not impacted by many of unit specific parameters such as sulfur content, ash content, etc. In this case, CPED methodology doesn't provide much more benefits on improving the accuracy of emission estimates to those species. In the meanwhile, coal-fired power plants contribute very small fraction to national total emissions (e.g., less than 1% of total CO emissions in 2010 estimated by Y. Zhao et al. (2013)). We have clarified this in the Sect. 2 of the manuscript. Power plants are significant sources of PM₁₀ emissions. We have added PM₁₀ estimates in the revised manuscript.

(2) What is difference/relationship between this study and the MEIC 1.2, 1.0 or MIX inventories? Does this paper advance those inventories? Is this paper one part of those inventories (which one)? Please specify in the paper.

Response: The CPED methodology developed in this work has been incorporated in both MEIC and MIX inventories. Briefly, the early version of CPED was used to both MEIC 1.0 and 1.2, and MIX used MEIC 1.0 for China. We have clarified the relationship in the Sect. 3.6 of the revised manuscript.

(3) Please make this inventory data set open to public, so that the scientific community is able to utilize.

Response: We have made the data open to public during the development of CPED. The early version of CPED has been integrated into the MEIC (Multi-resolution

Emission Inventory for China) database (both MEIC 1.0 and 1.2), which is available at the following website: <http://www.meicmodel.org/>. The most recent version of CPED (documented in this paper) will be incorporated to the next version of MEIC.

(4) Emissions were estimated at unit level for 2005-2010, however, priori to 2005, many parameters were extrapolated and assumed. So I suggest the authors make statements in the paper more clear about this difference.

Response: Thanks. We have clarified this in the Sect. 2.1 of the revised manuscript.

Specific comments:

(1) P18789, 1–3: what is the meaning of “because of a lack of detailed underlying data”?

Response: We replaced “detailed underlying data” with “underlying data such as detailed activity rates and local measured emission factors” in the revised manuscript.

(2) P18789, 11–12: what is the citation of “32% of CO₂, 33% of SO₂, 33% of NO_x, and 6% of PM_{2.5} in 2010”?

Response: The reference of Y. Zhao et al. (2013) has been added in the revised manuscript.

(3) P18791, 22: how much totally is the number of coal-fired electric generating units in mainland China?

Response: The total number is 7657. We have revised the statement in the revised manuscript.

(4) P18793, 11–14: Actually, the operation hour for each unit was not got from database but from disaggregation.

Response: Operation hours for each unit from 2005–2010 were obtained from database, but from disaggregation prior to 2005. While monthly profiles of each unit were derived from disaggregation.

(5) P18792–18792, Section 2.1: many data were extrapolated from years after 2000 to years 1990–2000. First, how robustness are these extrapolations? Second, the authors should emphasize emission estimates before 2000 are based on extrapolation rather than real data.

Response: Extrapolations are constrained by the provincial total coal consumptions and electricity productions, which ensures the reliability of total emission estimates at provincial level. Taking one unit as example, we have provided uncertainty estimates for the unit for both 2000 and 2010 in Sect. 4.1. Uncertainty ranges for 2000 estimates are significantly larger than for 2010 estimates (Table 6). In the Sect. 2.1 of the revised manuscript, we added a sentence to indicate the higher uncertainties in emission estimates before 2000.

(6) P18794, 20–23: “Surveys and satellite observations confirmed that some of the

early installed FGD facilities were not actually in operation prior to 2008”. Does this influence the final estimates much?

Response: The phenomenon may induce an underestimation of SO₂ emissions from 2005 to 2007. The FGD penetration was 12.2%, 29.5% and 49.9% for 2005, 2006 and 2007 respectively. Assuming 20% of FGD did not operate properly, national total emissions could increase by 2%, 4% and 9% for 2005, 2006 and 2007 respectively. In the Sect. 4.1 of the revised manuscript, we have discussed this as a potential source of uncertainties.

(7) P18797, 13–16: Do these values of “25.8 and 26.7 kg-C GJ⁻¹” differ from the values recently published by Liu et al., Nature, 2015? If yes, country-specific data are more appropriate.

Response: The coal carbon content used in CPED is very close (2% difference) to that in Liu et al. (2015).

(8) P18802, section 3.2.3: why did not the authors estimate PM₁₀? How about the changes in PM₁₀ during 1900–2010?

Response: PM₁₀ estimates have been added in the revised manuscript.

(9) P18807, section 4.2: what is the difference between this study and MEIC 1.0, MEIC1.2, MIX inventories? Please specify.

Response: See responses above.

(10) P18832, Figure 9, Figure 10, Figure 13: did you estimate emissions in Taiwan? Right now, the figures look like there are no emissions of these four compounds in Taiwan. If not, please specify and change the color.

Response: Thanks for pointing out this. The CPED database doesn't cover Taiwan. We have changed the color in Figure 9, Figure 10 and Figure 13 in the revised paper.

Reference

Liu, Z., Guan, D., Wei, W., Davis, S. J., Ciais, P., Bai, J., Peng, S., Zhang, Q., Hubacek, K., Marland, G., Andres, R. J., Crawford-Brown, D., Lin, J., Zhao, H., Hong, C., Boden, T. A., Feng, K., Peters, G. P., Xi, F., Liu, J., Li, Y., Zhao, Y., Zeng, N., and He, K.: Reduced carbon emission estimates from fossil fuel combustion and cement production in China, *Nature*, 524, 335–338, 2015.

Zhao, Y., Zhang, J., and Nielsen, C. P.: The effects of recent control policies on trends in emissions of anthropogenic atmospheric pollutants and CO₂ in China, *Atmos. Chem. Phys.*, 13, 487–508, doi:10.5194/acp-13-487-2013, 2013.

inventory.

(3) Presently, the research results about emissions from China's coal-fired power plants are one of the most comprehensive emission inventories in China. Based on the emission inventories, the authors are recommended to add some related discussion about integrated control suggestions for minimizing diminish the final stack discharges from coal-fired power plants of China, such as promotion of ultra-low emission units, which will be interesting to the international reader of ACP and policy makers.

Response: We thank the reviewer for the constructive suggestion. We added a paragraph in Sect. 5 to discuss the emission reduction potential in China's power plant sector, including promotion of ultra-low emission units, decommission of flue gas bypass system, and strengthening supervision and management, etc.

(4) With regard to $PM_{2.5}$ emissions, the spray slurry in scrubber of wet FGD system can scrubber part of PM, however, some of gym produced of SO_2 removal can be emitted as gym rain from the stack, which is a concern for many of units installed with limestone-gym FGD. I recommend this point should be properly addressed when considering the effects of FGD on $PM_{2.5}$ emissions.

Response: Thanks for pointing out this. We analyzed the influence of "gypsum rain" on $PM_{2.5}$ emissions in the Sect.4.1 of the revised manuscript. The assumption of $PM_{2.5}$ removal efficiency for wet FGD may have underestimated $PM_{2.5}$ emissions for wet limestone-gypsum FGD. Particulate matters in desulfurizers of the spray slurry from scrubbers of wet FGD are likely to exhaust from stacks along with plumes. These particulate matters would offset $PM_{2.5}$ emissions absorbed by scrubbers of wet FGD (Meij and te Winkel, 2004). In the revised manuscript, we conducted a sensitivity analysis to evaluate the effect of the assumption on $PM_{2.5}$ emissions. By assuming 10% changes of $PM_{2.5}$ emissions are induced by gypsum spray (Meij and te Winkel, 2004), $PM_{2.5}$ emissions could be increased by 0.3% in 2005 and 6.4% in 2010, depending on the penetrations of wet FGD.

(5) Line 10-12 on 18789: What are the sources of these air pollutant emissions? The references citation should be cited clearly.

Response: The reference of Y. Zhao et al. (2013) is added in the revised manuscript.

(6) Line 8 on Page 18792: how did the parameter "f" determine for each unit? It is critical for obtaining the monthly profiles of air pollutants for each unit, which should be clearly stated to make it more clarity.

Response: We further clarified the determination of the parameter "f" in the Sect. 2.1 of the revised manuscript, as follows:

The monthly fraction of annual electricity generation (f) is quantified by province, due to the lack of data at unit level. For 2003–2010, f was derived from the statistics (NBS, 2013) and was applied to each unit with adjustments if the unit was commissioned or decommissioned within that year, following Eq.(1). For the years prior to 2003, a

monthly climatological profile of the 2003–2007 average was used.

$$f_m = \frac{\gamma_m F_m}{\sum_{m=1}^{12} \gamma_m F_m} \quad (1)$$

where m represents the month. f and F is the monthly fraction of annual electricity generation at unit and province level respectively. γ is the state factor for the unit; $\gamma=1$ when the unit has been commissioned and in operation, otherwise $\gamma=0$.

(7) Line 10-16 on Page 18795: it might be true that some of SCR were not put into operation before 2010 owing to poor inspection. However, since most of these units are built in Beijing, YRD, and PRD regions, to improve the regional air quality where some large-scale international activities have been hold, such as 2008 Beijing Olympic, 2010 Shanghai Expo and 2010 Guangzhou Asia Games. Thus, assuming all of these DE-NO_x devices are not put into operation may overestimate the emissions. This point is recommended to be considered for the uncertainties analysis.

Response: In the Sect. 4.1 of the revised manuscript, we quantified the uncertainties induced by the assumption that the de-NO_x devices were not in operation until 2010. By assuming that de-NO_x devices were put into operation in Beijing, Shanghai and Guangdong in 2010, NO_x emission estimates could be reduced by 67 Gg (1% of total), indicating our assumptions have small impacts on national total NO_x emission estimates.

(8) The uncertainties of historical emissions of these four species are recommended to give more detailed discussion.

Response: Thanks for the suggestion. We have strengthened the discussion of uncertainties in the Sect.4.1 of the revised manuscript, as follows.

The uncertainty ranges narrowed gradually from 1990 to 2010, representing the improved knowledge of the underlying data over time. The uncertainty ranges declined from -36~38%, -24~26%, -43~55%, -32~39% and -24~27% in 1990 to -22~23%, -15~15%, -31~38%, -26~30% and -15~16% in 2010 for SO₂, NO_x, PM_{2.5}, PM₁₀ and CO₂ respectively. As discussed in Sect. 2, many of the input data in the CPED in 1990 were determined by extrapolations and assumptions associated with high uncertainty, whereas the uncertainty ranges for the 2010 emission estimates are significantly reduced because of the extensive use of unit-specific data. The unit-specific annual coal use in 2010 contributed to the improved accuracy for all four species. In addition, a better understanding of sulfur content and removal efficiency of FGD, coal type, ash content and heating value of coal for each unit in 2010, on which the accuracy of SO₂, NO_x, PM and CO₂ emission factors depend respectively, is the primary reason for the narrowed uncertainties for corresponding species.

Reference

Liu, F., Beirle, S., Zhang, Q., Dörner, S., He, K. B., and Wagner, T.: NO_x lifetimes and emissions of hotspots in polluted background estimated by satellite observations, *Atmos. Chem. Phys. Discuss.*, 15, 24179–24215, doi:10.5194/acpd-15-24179-2015, 2015.

Meij, R., and te Winkel, B.: The emissions and environmental impact of PM10 and trace elements from a modern coal-fired power plant equipped with ESP and wet FGD, *Fuel Process. Technol.*, 85, 641–656, 2004.

National Development and Reform Commission (NDRC): Clean coal-fired power plants action plan (2014–2020), available at: http://www.sdpc.gov.cn/gzdt/201409/t20140919_626240.html (last access: September 10, 2015), 2014 (in Chinese).

Zhao, Y., Zhang, J., and Nielsen, C. P.: The effects of recent control policies on trends in emissions of anthropogenic atmospheric pollutants and CO₂ in China, *Atmos. Chem. Phys.*, 13, 487–508, doi:10.5194/acp-13-487-2013, 2013.

1 **High-resolution inventory of technologies, activities,**
2 **and emissions of coal-fired power plants in China from**
3 **1990 to 2010**

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22 **Abstract**

23 This paper, which focuses on emissions from China's coal-fired power plants during
24 1990–2010, is the second in a series of papers that aims to develop high-resolution
25 emission inventory for China. This is the first time that emissions from China's
26 coal-fired power plants were estimated at unit level for a 20-yr period. This inventory
27 is constructed from a unit-based database compiled in this study, named the China
28 coal-fired Power plant Emissions Database (CPED), which includes detailed
29 information on the technologies, activity data, operation situation, emission factors,
30 and locations of individual units and supplements with aggregated data where
31 unit-based information is not available. Between 1990 and 2010, compared to a 479%
32 growth in coal consumption, emissions from China's coal-fired power plants
33 increased by 56%, 335% and 442% for SO₂, NO_x and CO₂, respectively, and
34 decreased by 23% and 27% for PM_{2.5} and PM₁₀ respectively. Driven by the
35 accelerated economy growth, large power plants were constructed throughout the
36 country after 2000, resulting in dramatic growth in emissions. Growth trend of
37 emissions has been effectively curbed since 2005 due to strengthened emission control
38 measures including the installation of flue-gas desulfurization (FGD) systems and the
39 optimization of the generation fleet mix by promoting large units and
40 decommissioning small ones. Compared to previous emission inventories, CPED
41 significantly improved the spatial resolution and temporal profile of power plant
42 emission inventory in China by extensive use of underlying data at unit level. The
43 new inventory developed in this study will enable a close examination for temporal
44 and spatial variations of power plant emissions in China and will help to improve the
45 performances of chemical transport models by providing more accurate emission data.

46

47 1. Introduction

48 Bottom-up emission inventories, which are compiled from activity rates and emission
49 factors, provide crucial information for understanding the variability of atmospheric
50 compositions and for regulating climate and air quality policies. However, the current
51 understanding of anthropogenic emissions in China is insufficient because of a lack of
52 underlying data **such as detailed activity rates and local measured emission factors**
53 (Zhao et al., 2011). This paper is the second in a series that aims to reduce these
54 uncertainties and to improve the spatial and temporal resolution of bottom-up
55 emission inventories in China. The first paper developed a high-resolution emission
56 map for on-road vehicles (Zheng et al., 2014), and this paper focuses on coal-fired
57 power plants.

58 Power plants consumed approximately half of the total coal production in China over
59 the past decade (China Energy Statistical Yearbook, National Bureau of Statistics
60 (NBS), 1992–2011) and contributed significantly to the total national emissions of
61 greenhouse gases and air pollutants (32% of CO₂, 33% of SO₂, 33% of NO_x, and 6%
62 of PM_{2.5} in 2010, **Y. Zhao et al. (2013)**). Therefore, developing a coal-fired power
63 plant emission inventory with high spatial and temporal resolution can significantly
64 improve the accuracy of the anthropogenic emission inventory in China. In the
65 meanwhile, because the power plant sector plays a key role in energy and
66 environmental policies, a well-developed power plant database with accurate energy
67 consumption and emission data could help to guide future policies and evaluate the
68 dynamic changes in emissions induced by those policies.

69 As one of the major anthropogenic emitting sources, coal-fired power plant emissions
70 in China have been estimated in many national, regional, and global inventories. Early
71 studies (Kato and Akimoto, 1992; Klimont et al., 2001; Hao et al., 2002; Ohara et al.,
72 2007) used yearly activity data with fixed emission factors to estimate emissions,
73 which ignored the fact that the net emission rates were changing rapidly with the
74 emergence of new technologies into the market. In recent studies, technology-based
75 methodologies and locally measured emission factors were used to represent the

76 dynamic changes in emissions, which improved the estimates of the magnitudes of
77 and trends in power plant emissions throughout China (e.g., Zhang et al., 2007, 2009a;
78 Klimont et al., 2009; Lei et al., 2011; Klimont et al., 2013; Tian et al., 2013; Y. Zhao
79 et al., 2013).

80 In addition to the accuracy of the magnitudes, accurate information for each
81 generation unit (i.e., location, emission) is also critical for a power plant inventory
82 because power plant emissions are typically large, and improper treatment may lead
83 to significant bias in the spatial distribution of emissions. Owing to the difficulties in
84 acquiring information for all of the power plants in China, many bottom-up
85 inventories only identified emissions from large power plants and allocated them
86 according to their latitude and longitude coordinates, whereas emissions from other
87 small units were distributed as area sources (e.g., Streets et al., 2003; Ohara et al.,
88 2007; Zhang et al., 2009a; Lu et al., 2011). For the first time, Zhao et al. (2008) used
89 unit-level coal consumptions to calculate emissions of individual electric generation
90 units for the years of 2000 and 2005 and assigned them to each location. Subsequent
91 studies developed unit-based power plant emission inventories for NO_x for the period
92 of 2005–2007 (Wang et al., 2012) and for SO₂, NO_x, particulate matter and PM_{2.5} for
93 2011 (Chen et al., 2014). The Carbon Monitoring for Action (CARMA) database
94 (Wheeler and Ummel, 2008), a global power plant database at the factory level, has
95 been widely used in bottom-up emission inventories to allocate power plant emissions
96 (EC-JRC/PBL, 2011; Oda and Maksyutov, 2011; Kurokawa et al., 2013; Wang et al.,
97 2013). However, the accuracy of the emission strengths and locations in the CARMA
98 database is questionable given that it is not a scientific-level dataset that has
99 undergone critical evaluation (Oda and Maksyutov, 2011; Gurney, 2012).

100 There are two major deficiencies in the current power plant inventories throughout
101 China for revealing emissions at the unit level. First, owing to the lack of detailed
102 information at the unit level, emissions from each plant are generally divided by the
103 provincial totals according to capacity (e.g., Zhang et al., 2009a; Lu et al., 2011),
104 which ignores the differences in the emission rates among units introduced by

105 different technologies. Second, in a rapidly developing country such as China,
106 emission factors for a given power plant may change over time as new combustion or
107 emission control technologies are applied following the implementation of new
108 emission standards. Therefore, these time-dependent parameters should be included
109 dynamically when constructing an accurate emission trend for the power plants in
110 China.

111 The purpose of this study was to develop a high-resolution inventory of the
112 technologies, activity rates, and emissions of coal-fired power plants in China for the
113 period of 1990–2010 using extensive underlying data at the unit level, supplemented
114 with aggregated data where unit-based information is not available. This is the first
115 time that coal-fired power plant emissions in China were estimated for each unit from
116 the bottom-up for a two-decade period. We construct a unit-based database, called the
117 China coal-fired power plant emissions database (CPED), by collecting information
118 regarding the technologies, activity data, emission factors, and locations of individual
119 electricity generating units. To improve the accuracy of the emission estimates at the
120 unit level, the database developed in this study includes not only the type and removal
121 efficiency of emission control equipment for each unit but also the operating
122 conditions of the equipment (i.e., when the equipment was commissioned).

123 Based on the unit-specific parameters from the CPED (e.g., unit capacity, boiler type,
124 operation and phasing-out procedures, the sulfur content and ash content of coal, the
125 type of emission control equipment and the time at which the equipment was
126 commissioned, along with its removal efficiency), the SO₂, NO_x, fine particulate
127 matter (PM_{2.5}), **PM₁₀** and CO₂ emissions were estimated on a monthly basis for each
128 coal-fired power generation unit over the period of 1990–2010. **CO, VOC, BC and**
129 **OC emissions were not estimated in this work because coal-fired power plants**
130 **contributed very small fractions to national total emissions of these species (e.g., less**
131 **than 1% of total CO emissions in 2010 estimated by Y. Zhao et al. (2013)).**

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133 2. Unit-based Methodology and Data

134 The CPED database developed in this study consists of 7657 coal-fired electric
135 generating units in mainland China, including ~5700 units in use in 2010 and ~1900
136 units retired since 2005. The SO₂, NO_x, PM_{2.5}, PM₁₀ and CO₂ emissions from a
137 specific unit in a given month from 1990 to 2010 were estimated using the following
138 equation:

$$139 \text{Emis}_{s,y,m} = U \times P \times (H_0 / H_y) \times T_y \times f_{m,y} \times \text{EF}_{s,k,y} \times \prod_n (1 - \eta_{n,s} \times \tau_{n,m,y}) \quad (1)$$

140 where s represents the emission species, k represents the boiler type, n represents the
141 emission abatement technology type, y represents the year, and m represents the
142 month. U is the unit capacity, in MW, P is the coal consumption rate presented in
143 grams coal equivalent per kWh supplied (gce/kWh), H is the heating value of coal
144 used for each unit in kJ/g, H_0 is the heating value of standard coal, which is 29.27
145 kJ/gce, and the ratio of H_0 to H converts the coal equivalent (gce) to the physical
146 quantity of coal (gram). T is the annual operation in hours, the product of U and T
147 is the annual electricity generation, f is the monthly fraction of annual electricity
148 generation, and EF is the unabated emission factor, in g/kg-coal. The parameter η
149 is the removal efficiency of the abatement equipment, and τ is the state factor for the
150 abatement equipment; $\tau = 1$ when the equipment is present and running, otherwise $\tau =$
151 0.

152 2.1. Activity Rates

153 Detailed activity data are available for each generation unit for the period of
154 2005–2010 from China’s Ministry of Environmental Protection (MEP; unpublished
155 data, referred to hereafter as MEP-database). We used the MEP-database as the basis
156 of deriving the activity rates for each unit for the period of 1990–2010 from a
157 combination of different datasets. The capacity (U) and operational status (when the
158 unit was commissioned/decommissioned) for each unit were collected from the
159 MEP-database and the National Development and Reform Commission (NDRC,
160 2013). The annual coal use and power generation of each unit from 2005 to 2010 were

161 also obtained from the MEP-database and were used to calculate the coal
162 consumption rate (P) for each unit. The details about the generation unit fleet mix
163 according to capacity size and efficiency are presented in Sect. 3.1.

164 The heating value of the coal (H) used for each unit in 2010 was obtained from the
165 MEP-database. In other years for which the unit-level data are not available, the
166 average heating values of the coal used in power plants were derived by year and by
167 province from the energy statistics (NBS, 1992–2011) and were then adopted to scale
168 the 2010 value of each unit to the corresponding years. The heating values of coal
169 decreased remarkably since 2007 (from 20.0 kJ/g-coal in 2007 to 18.8 kJ/g-coal in
170 2010 as the national average), indicating the downgraded coal quality in the power
171 sector due to a shortage of coal induced by a surge of electricity demand in recent
172 years (Liu 2007; Shen and Song, 2010). **Table S3 of the supplemental information**
173 **summarizes the provincial average of coal consumption rate and heating value for the**
174 **year 2010.**

175 The annual operating hours (T) for each unit from 2005–2010 were obtained from the
176 MEP-database. In other years for which the unit-based data are not available,
177 operating hours were scaled from the 2005 data according to the ratio of the
178 provincial average operating hours in 2005 and the corresponding year. The provincial
179 average operating hours before 2005 were estimated from the provincial total coal
180 consumptions (NBS, 1992–2011) and the product of the corresponding unit capacity
181 and the coal consumption rate obtained from our database. **It should be noted that**
182 **emissions estimates priori to 2005 are more uncertain because the extrapolated**
183 **parameters were used.**

184 **The monthly fraction of annual electricity generation (f) is quantified by province, due**
185 **to the lack of data at unit level.** For 2003–2010, f was derived from the statistics (NBS,
186 2013) and was applied to the units with adjustments if the unit was commissioned or
187 decommissioned within that year, following Eq.(2). For the years prior to 2003, a
188 monthly climatological profile of the 2003–2007 average was used.

189
$$f_m = \frac{\gamma_m F_m}{\sum_{m=1}^{12} \gamma_m F_m} \quad (2)$$

190 where m represents the month. f and F is the monthly fraction of annual electricity
191 generation at unit and province level respectively. γ is the state factor for the unit; $\gamma=1$
192 when the unit has been commissioned and in operation, otherwise $\gamma=0$.

193 Coordinates of each unit (latitude and longitude) were obtained from the MEP-dataset
194 and then individually validated using Google Earth to ensure that the accurate
195 locations are presented in the CPED.

196 2.2. Emission Factors

197 2.2.1. SO₂

198 The unabated SO₂ emission factors for a specific unit were estimated via the sulfur
199 mass balance approach using the following equation:

$$200 \quad EF_{SO_2,y} = 2 \times SCC_y \times (1 - Sr) \quad (3)$$

201 where y represents the year, EF_{SO_2} is the unabated SO₂ emission factor in g/kg, SCC is
202 the sulfur content of coal, and Sr is the fraction of sulfur retention in ash.

203 The SCC for each unit from 2005–2010 was obtained from the MEP-database. The
204 SCC ranges widely with a mean value of 0.95%. The SCC in the northeast power
205 plants is lowest, whereas the SCC in the central and south power plants is
206 significantly higher than that of plants in other regions, reflecting the different sulfur
207 content in coal production in the various regions (Tang, et al., 2008). For the years
208 before 2005, the SCC for each unit was scaled from 2005 data using the ratio of the
209 provincial average SCC in 2005 and the corresponding year. The provincial average
210 SCC before 2005 was calculated from the sulfur contents of coal production in each
211 province using the coal transportation matrix approach (Zhang et al., 2012). The
212 sulfur retention ratio was assumed to be 15% for all of the units (Zhang et al., 2009a;
213 Lu et al., 2010) because of the lack of unit-specific data.

214 Flue-gas desulfurization (FGD) systems have been widely installed in coal-fired
215 power plants in China since 2005. This is the most important step for the emission
216 reduction plan to reduce national SO₂ emissions by 10% during the 11th five-year

217 period (2005–2010). In this study, the operating conditions of FGD for each unit were
218 obtained from the MEP-database. The actual SO₂ removal efficiencies for each unit in
219 2010 were also obtained from the MEP-database and were applied to every year
220 because no data are available for the other years. The coal-consumption weighted
221 mean SO₂ removal efficiency of all FGD facilities in 2010 is 78%. Surveys and
222 satellite observations confirmed that some of the early installed FGD facilities were
223 not actually in operation prior to 2008 as the factories reported (Xu et al., 2009; Li et
224 al., 2010; Xu, 2011), implying that our assumption may underestimate the SO₂
225 emissions from 2005 to 2007 for some units. SO₂ emissions can also be removed from
226 wet scrubbers as a co-benefit of particulate matter removal. In this study, we assumed
227 that the removal efficiency of wet scrubbers for SO₂ is 20% (Yao, 1989; Xie, 1995).

228 **2.2.2. NO_x**

229 NO_x emission rates from coal-fired power plants vary significantly by boiler size,
230 combustion technology, and coal type. In this study, we classified the units into three
231 categories by size: large units (≥ 300 MW), medium units (≥ 100 MW and < 300 MW),
232 and small units (< 100 MW). We also classified the units into three categories by
233 combustion technology (traditional low-NO_x burner technology (traditional LNB),
234 advanced LNB, and without LNB (Non-LNB)) and into two categories by coal type
235 (bituminous and anthracite). Table 1 summarizes the measured NO_x emission factors
236 in China's coal-fired power plants from each category.

237 Selective catalytic reduction (SCR) and selective noncatalytic reduction (SNCR) are
238 two major de-NO_x technologies used in coal-fired power plants. In 2010, 194
239 coal-fired electric generation units (13% of the national total capacity) with a total
240 capacity of 84 GW were equipped with SCR or SNCR. However, the actual operating
241 conditions of the installed de-NO_x devices are questionable due to the lack of
242 inspections by local environmental protection bureaus before 2010. Our recent study
243 also found that satellite-recorded tropospheric NO₂ columns around the power plants
244 with de-NO_x devices were stable before 2010, indicating the poor operating
245 conditions of these devices (Wang et al., 2015). In this study, we assumed that the

246 de-NO_x devices were not in operation until 2010 by setting the state factor in Eq. (1)
247 to zero.

248 Prior to 2010, LNB technology was the only widely used technology in China's power
249 plants to reduce NO_x emissions. Beginning in 1997, the use of LNB technologies in
250 China's power plants increased, following the strengthened emission standards for
251 thermal power plants (State Environmental Protection Administration of China
252 (SEPA), 1996, 2003) in China. Since approximately 2005, newly established large
253 generation units have been widely equipped with advanced LNB technologies, i.e.,
254 the stereo-staged combustion technology (Zhang et al., 2009b) and the so-called
255 "double-scale" combustion technology, which can significantly reduce the emission
256 rates of NO_x. Recent measurements of China's coal-fired power plants confirmed that
257 NO_x emission rates from large units with advanced LNB technologies are remarkably
258 lower than units with traditional LNB technologies (e.g., Zhu et al., 2009; Zhu, 2011;
259 Cao and Liu, 2011; see Table 1).

260 Based on the discussion above, we assigned the appropriate LNB technology to each
261 generation unit according to the following assumptions, given that the LNB
262 information was absent from the MEP-database: (1) All large units constructed before
263 2006 are equipped with traditional LNB, and units constructed after 2006 are
264 equipped with advanced LNB; (2) medium units constructed after 1997 are equipped
265 with traditional LNB to meet the emission standards (SEPA, 1996), whereas units
266 constructed before 1997 are not equipped with LNB; and (3) no small units are
267 equipped with LNB during the study period. We then used the emission factors
268 presented in Table 1 to calculate the NO_x emissions for each unit.

269 **2.2.3. PM**

270 **PM emissions were estimated for two size fractions: PM_{2.5} and PM_{2.5-10} (PM with**
271 **diameter more than 2.5 μm but less than 10 μm, coarse particles).** The unabated
272 emission factor of **PM** was calculated using the following equation:

$$273 \text{EF}_{k,d} = \text{AC} \times (1 - ar_k) \times f_{k,d} \quad (4)$$

274 where k represents the boiler type, d represents the diameter range of PM; EF_d is the
275 emission factor of PM in diameter d , AC is the ash content of coal, ar is the mass
276 fraction of retention ash, and f_d is the mass fraction of PM in diameter d to the total
277 particulate matter in fly ash.

278 When calculating PM emissions, coal-fired generation units are classified into three
279 boiler types: pulverized coal boilers, circulating fluidized beds, and grate furnaces.
280 The boiler type information for each unit was obtained from the MEP-database. For
281 each boiler type, the fraction of retention ash was derived from the Greenhouse Gas
282 and Air Pollution Interactions and Synergies (GAINS) database (Klimont, et al., 2002;
283 Amann et al., 2011), with values of 20%, 44% and 85% for pulverized coal boilers,
284 circulating fluidized beds, and grate furnaces, respectively. The mass fraction of PM
285 in diameter d to total particulate matter in fly ash was derived from the GAINS
286 (Klimont, et al., 2002; Amann et al., 2011) and local databases (Zhao et al., 2010), as
287 presented in Table 2. The ash content of coal for each unit in 2010 was obtained from
288 the MEP-database and was applied to every year. Table S3 presents the provincial
289 average of coal sulfur content and ash content for the year 2010.

290 The four types of technologies used in power plants to remove particulate matter are
291 cyclones, wet scrubbers, electrostatic precipitators, and bag filters. The technology
292 type for each unit was obtained from the MEP-database. The removal efficiencies of
293 each technology were obtained from our previous study (Lei et al., 2011) and are
294 shown in Table 3. Particulate matter can also be removed via wet FGD as a co-benefit
295 of SO₂ removal. In this study, we assume the same PM_{2.5} removal efficiency for wet
296 FGD equipment as that for wet scrubbers (Zhao et al., 2010). The uncertainty of the
297 effect of the assumption on PM emissions was discussed in Sect.4.1.

298 **2.2.4. CO₂**

299 The emission factor for CO₂ was calculated using guidelines from the
300 Intergovernmental Panel on Climate Change (IPCC, 2006), as follows:

$$301 \quad EF_{CO_2,y} = A \times O \times 44 / 12 \times H_y \quad (5)$$

302 where y is the year, EF_{CO_2} is the CO₂ emission factor in g/kg, A is the carbon content
303 in kg-C/GJ, O is the oxidization rate, and H is the heating value in kJ/g-coal. In this
304 study, we used 25.8 and 26.7 kg-C/GJ for the carbon contents of bituminous and
305 anthracite coal, respectively, and 100% for the oxidization rate; these values were
306 obtained from the IPCC guidelines (IPCC, 2006). The data source of the coal heating
307 value is presented in Sect. 2.1.

308 **2.3. Uncertainty Analysis**

309 An uncertainty analysis was performed for our estimates using a Monte Carlo
310 approach. The term “uncertainty” in this study refers to the lower and upper bounds of
311 a 95% confidence interval (CI) around a central estimate. The Monte Carlo simulation
312 uses specified probability distributions for each input parameter (e.g., activity data,
313 emission factors) to generate random variables. The probability distribution of
314 emissions is estimated according to a set of runs (10,000 runs in this study) in a
315 Monte Carlo framework with probability distributions of the input parameters (Lu et al.,
316 2011; Zhao et al., 2011). Table S1 in the supplementary information summarizes
317 the probability distributions of all of the input parameters used to estimate the
318 uncertainties of the national total emission estimates. For parameters with adequately
319 measured data (e.g., NO_x emission factors), distribution functions were fitted from the
320 distributions of those data. Probability distributions of other parameters were obtained
321 from previous studies (Zhao et al., 2010, 2011; Lu et al., 2011) or were based on our
322 own discretion.

323 Uncertainties associated with emission estimates could vary with time. The
324 uncertainties for a unit in 1990 can be considered larger than the uncertainties in 2010,
325 for which all of the specific information is available in the CPED. In this study, we
326 also calculated the emission uncertainties of one selected generation unit for 2000 and
327 2010 to demonstrate the uncertainties at the unit level. The probability distributions of
328 the unit-level parameters are presented in Table S2 in the supplementary information.
329 In contrast to uncertainty analyses for national total emissions, we used discrete

330 distributions (i.e., “Yes/No” distributions) to represent the probability distributions of
331 the technologies, which represent situations in which our assumptions about the
332 technology for a specific unit are correct/incorrect.

333

334 **3. Results**

335 **3.1. Evolution of technologies in coal-fired power plants**

336 The energy efficiency of power plants in China has improved significantly over the
337 past two decades. As shown in Fig. 1, the average coal consumption per unit
338 electricity supplied decreased from 407 gce/kWh in 1990 to 327 gce/kWh in 2010,
339 representing an improvement of 20% in energy efficiency over 20 years. This
340 significant change could be attributed to the measures imposed by the Chinese
341 government to encourage large-scale power units and to decommission small units.
342 Figure 1 also presents the variation trend in the share of units of different sizes from
343 1990 to 2010. The share of the unit capacity of large units (≥ 300 MW) increased
344 sharply from 18% in 1990 to 74% in 2010, whereas the share for small units (< 100
345 MW) dropped to 9%. In particular, the construction rate of large units equal to or
346 larger than 600 MW began to accelerate after 2005. The capacity of units equal to or
347 larger than 600 MW was only 46 GW in 2005 but increased to 262 GW by 2010,
348 accounting for 39% of the national total capacity.

349 Figure 2 further examines the measures taken to drive the rapid change from
350 2005-2010. To fulfill the increasing demand for electricity, China constructed 417
351 GW capacities from 2005–2010, of which 83% were large units. Fig. 2(a) shows the
352 growth of new power units since 2005. During this time, large units began to account
353 for a greater share of new units. For all of the newly constructed units, the percentage
354 of large units increased significantly from 29% to 49% from 2006 to 2010, whereas
355 the percent of small units decreased from 57% to 41%. In addition, the construction of
356 new power generation capacity decreased from 86 GW in 2006 to 66 GW in 2010. In
357 the meanwhile, China has taken measures to phase out low-efficient power plants.

358 Figure 2(b) illustrates that small units, especially those smaller than 25 MW,
359 constitute the largest component of retired units, accounting for 89% of the number of
360 retired units in 2006. However, this ratio dropped to 62% in 2010 because the
361 phase-out strategy gradually pursued larger units once the majority of units smaller
362 than 25 MW had been phased out. The average capacity of the units retired in 2010
363 was 40 MW, three times the value in 2006 (13 MW).

364 The great effort from 2005 to 2010 to construct large units and phase out small units
365 significantly improved China's power plant energy efficiency, which is indicated by
366 the shift of the coal consumption rate shown in Fig. 3. Figure 3 compares the number
367 of plants by coal consumption rate (gce/kWh) in 2005 and 2010. In 2005, 62% of
368 power plants in China had a coal consumption rate of 400-700 gce/kWh, and 20% of
369 power plants had a consumption rate greater than 700 gce/kWh. In 2010, 57% of
370 power plants in China had a coal consumption rate of 400 gce/kWh or lower.
371 Generally, large units consume less coal than small units for the same amount of
372 electricity generated because of the more advanced combustion technology used in
373 larger units such as supercritical and ultra-supercritical. From 2005 to 2010, with the
374 increase in the number of large units, the average coal consumption rate decreased
375 from 356 gce/kWh to 327 gce/kWh, representing an 8% total efficiency improvement
376 from 2005–2010.

377 **3.2. Inter-annual Emissions**

378 Figure 4 and Table 4 summarizes the emissions of each species from China's
379 coal-fired power plants during 1990–2010. The total coal consumptions in China's
380 coal-fired power plants increased significantly by 479% in China from 1990 to 2010,
381 whereas SO₂ emissions from the power plants increased by 56%, NO_x emissions
382 increased by 335%, CO₂ emissions increased by 442%, PM_{2.5} emissions decreased by
383 23%, and PM₁₀ emissions decreased by 27% during the same period, indicating that
384 significant technological changes occurred in the power sector. Table 4 also presents
385 the variation in technology penetration rates and emission factors of coal-fired power

386 plants from 1990 to 2010.

387 **3.2.1. SO₂**

388 Figure 4 shows the SO₂ emissions from power plants estimated in this study. From
389 1990 to 2005, SO₂ emissions increased at an annual rate of 8%, driven by the
390 ever-increasing demand for electricity, at a growth rate of 10%. The improved energy
391 efficiency and co-benefit of wet scrubbers on SO₂ removal slightly mitigated the
392 emission growth trend. In 2005, to control emissions, China began to require the
393 installation of FGD in power plants (Table 4). Therefore, the SO₂ emissions peaked at
394 16.7 Tg in 2006 and began to decrease sharply. By 2010, 84% of the total unit
395 capacity in our database was equipped with FGD, which was estimated to reduce SO₂
396 emissions to 7.7 Tg, 54% lower than the 2006 emission level.

397 Figure 5 presents the FGD installation process. As shown in Fig. 5, in 2006, FGD was
398 primarily installed for new units, and the share of unit capacity installed with FGD
399 was 69% for new units, whereas it was only 15% for those over 10 years old.
400 Influenced by the premium price for desulfurized electricity and the penalties incurred
401 for non-desulfurized electricity since 2007 (Xu et al., 2009), the deployment of FGD
402 sharply increased for new and aged units. As Fig. 5 shows, there was no difference in
403 the FGD installation ratio between new and aged units younger than 20 years old in
404 2010, and the share of the unit capacity with FGD reached 63% for units over 10
405 years old.

406 However, the SO₂ removal efficiencies vary among the different units. As presented in
407 Fig. 6, FGD equipped on larger units exhibited better SO₂ removal efficiencies than
408 that on small units. In 2010, the average SO₂ removal efficiencies were approximately
409 80% for large units but only 60% for small units. Figure 7 presents the cumulative
410 ratio of SO₂ emissions by unit size for 2005 and 2010. The cumulative ratio of the
411 unit capacity was comparable to that of the SO₂ emissions in 2005 (Fig. 7a), but they
412 differed significantly in 2010 (Fig. 7b). The capacity share of small units decreased
413 from 20% in 2005 to 9% in 2010, but the contribution to the total SO₂ emissions

414 remained unchanged at ~20%. Before 2005, the emission contribution to SO₂ of a
415 power unit was largely dependent on its capacity because desulfurization devices were
416 seldom employed at that time. Thus, the cumulative ratios of the unit capacity and
417 SO₂ emissions could be similar. However, in 2010, 92% of large units were equipped
418 with FGD, which is considerably higher than the number of small units (52%). In
419 addition, large units tend to have higher SO₂ removal efficiencies. In 2010, large units
420 contributed to 55% of the total SO₂ emissions in 2010 while comprising 76% of the
421 total capacity.

422 **3.2.2. NO_x**

423 As shown in Fig. 4, NO_x emissions from power plants continued to increase from
424 1990 to 2010, except for the period of 2007–2009. NO_x emissions from power plants
425 increased by a factor of 3.4 from 1990 to 2010, from 1.9 Tg (all of the values herein
426 are calculated as NO₂) in 1990 to 8.3 Tg in 2010. This dramatic growth was largely
427 driven by the increasing electricity demand and was partially offset by the installation
428 of LNB. Our study suggests that the average NO_x emission factor (in g/kg of coal)
429 slightly decreased at an annual rate of 1% from 1990 to 2005 with increasing LNB
430 penetrations (Table 4). From 1990 to 2005, NO_x emissions increased at an annual
431 growth rate of 8.6%, comparable to the 9.4% annual growth rate of coal consumption
432 during the same period. After 2005, the decreased rate of average NO_x emissions
433 accelerated (at 3% per year) because of the higher NO_x removal efficiencies of
434 advanced LNB technologies compared with traditional LNB. From 2005 to 2010,
435 NO_x emissions increased by 126%, which is remarkably lower than the 150% increase
436 in coal consumption. Owing to the decline in emission factors and the reduction in
437 electricity demand led by the global economic crisis, NO_x emissions decreased in
438 2008 and 2009 but increased again in 2010 at a growth rate of 9% after recovery from
439 the economic crisis.

440 **3.2.3. PM**

441 PM_{2.5} and PM₁₀ emissions from power plants decreased from 1.08 and 1.79 Tg in

442 1990 to 0.83 and 1.32 Tg in 2010 respectively, with two fluctuating peaks occurring in
443 1996 and 2005, which were due to the combined effect of electricity demand and
444 environmental regulations. Our estimates for the period of 1990–2005 are generally
445 consistent with our previous estimates (Lei et al., 2011). The decline of emissions
446 after the first peak was driven by the technology renewal progress following the
447 implementation of the first emission standards for power plants in 1996 (SEPA, 1996),
448 and the deceleration of the Chinese economy. PM emissions rebounded after the 1998
449 financial crisis but decreased again after 2005, in compliance with the implementation
450 of stricter emission standards for power plants (SEPA, 2003). PM_{2.5} and PM₁₀
451 emissions decreased by 40% and 47% from 2005–2010 respectively, which may be
452 due to the following reasons. First, small units with poorly efficient PM emission
453 control facilities were phased out from the unit fleet. Second, electrostatic
454 precipitators and bag filters with high removal efficiencies were widely equipped in
455 generation units under the requirement of the new emission standards. In addition,
456 FGD installation further removed PM emissions from the end-pipe. Due to the
457 combination of these three factors, the average PM_{2.5} and PM₁₀ emission factors
458 decreased by 60% and 65% from 2005–2010 respectively, completely offsetting the
459 effect of the 50% increase in coal consumption.

460 **3.2.4. CO₂**

461 Of the examined species emitted from power plants, CO₂ emissions increased most
462 rapidly from 1990 to 2010 because, in contrast to SO₂, NO_x, and PM_{2.5}, no control
463 measures were implemented to remove CO₂. We estimated that China's coal-fired
464 power plants emitted 2.8 Pg CO₂ in 2010, an increase of 442% compared with
465 emissions in 1990. The increase is in line with the 574% growth in electricity
466 generation (China Energy Statistical Yearbook, NBS, 1992–2011) but is slightly offset
467 by the improved energy efficiency resulting from the spread of large and efficient
468 units. Due to the improvement in energy efficiency, CO₂ emissions per unit of
469 electricity supplied were reduced by 20% from 1990 to 2010, which is a great
470 achievement, although far from constraining the growth of CO₂ emissions.

471 **3.3. Evaluation of Major Policies for Emission Mitigation**

472 This section evaluates the effects of the major emission control measures on reducing
473 SO₂, NO_x, PM_{2.5} and CO₂ emissions during the 11th five-year period (2005–2010). As
474 described in Sect. 3.1, China primarily implemented two policies for power plants
475 during this period, including the installation of FGD and the optimization of the mix
476 of generation unit fleets by promoting large power plants and decommissioning small
477 plants. We developed two hypothetical scenarios to evaluate the effects of these two
478 policies on emission mitigation, as follows: (1) Scenario I: we assumed that China did
479 not adjust its fleet mix, i.e., its distribution of capacity size. In this scenario, the
480 amount of newly-built capacity is the same as the actual case, but the fleet mix was
481 assumed unchanged during 2005 and 2010. (2) Scenario II: based on Scenario I, we
482 further assumed that no new FGD installations were performed after 2005.

483 Figure 8 compares the emission differences between the hypothetical Scenarios I and
484 II and the actual cases during 2005 and 2010. Restructuring the unit fleet resulted in
485 coal savings by improving efficiency, which contributed to emission abatement for all
486 of the species. In 2010, the restructuring aided in the reduction of 83.7 Tg of coal use,
487 4.3 Tg SO₂, 1.8 Tg NO_x, 0.4 Tg PM_{2.5} and 238.6 Tg CO₂ emissions compared with the
488 hypothetical Scenario I.

489 The differences between the hypothetical Scenario I and Scenario II represent the
490 effects of FGD installations. As shown in Fig. 8, FGD installation was a significant
491 contributor to emission mitigation of SO₂ and PM_{2.5}. During the 6-year period from
492 2005 to 2010, FGD installation was estimated to reduce 51.6 Tg of cumulative SO₂
493 emissions or 36% of the cumulative SO₂ emissions from power plants compared with
494 the hypothetical Scenario II. In 2010, FGD installation prevented 16.3 Tg of SO₂
495 emissions, a value that is 2.1 times higher than the total actual emissions. In addition,
496 FGD facilities aided in reducing PM_{2.5} by 0.54 Tg in 2010, owing to the co-benefit of
497 wet-FGD on particulate matter removal.

498 3.4. Spatial Distribution of Emissions

499 Table 5 summarizes the unit fleet mix by capacity size and technology penetration
500 rates, as well as the emission factors of China's six large interprovincial power grids,
501 which are named according to the regions they serve, as follows: Northeast China,
502 North China, Central China, East China, Northwest China, and South China. A
503 significant decrease in the emission factors of each of the **five** species can be observed
504 for all of the power grids from 2005 to 2010, especially for SO₂ and **PM**, which is
505 consistent with the national trend. The emission factors are different among the grids
506 due to their different mix of unit fleets, fuel qualities, and penetration of emission
507 control technologies. Of the six grids, the east and central grids exhibited the lowest
508 CO₂ emission factors in 2010, primarily due to their high percentage of large units in
509 the generation mix (the capacity share of units larger than 300 MW was more than
510 75% in 2010) and the higher combustion efficiency of large units. The variations of
511 SO₂ emission factors among the grids represent the differences in FGD penetration
512 and the sulfur content of coal. The SO₂ emission factors for the south and central grids
513 are higher than the other grids due to the high sulfur content of coal. The FGD
514 penetration rate of the northeast grid was significantly lower than that of the south
515 grid in 2010 (60.1% in the northeast versus 92.7% in the south). However, the
516 northeast grids had a lower SO₂ emission factor (2.23 g/kWh in the northeast versus
517 3.41 g/kWh in the south) due to the differences in the sulfur content of coal between
518 the two regions. The PM_{2.5} emission factors varied remarkably due to the regional
519 differences in the penetration rates of efficient PM_{2.5} removal facilities (electrostatic
520 precipitators and bag filters). In 2010, the average PM_{2.5} emission factor in the
521 northeast grid was more than two times higher than that of the east grid due to its
522 lower penetration rates of electrostatic precipitators (89.0% versus 96.2%). Because
523 an electrostatic precipitator has very high removal efficiency for PM_{2.5} (93%)
524 compared with wet scrubbers (50%) and cyclones (10%), small differences in
525 technology penetration among regions could result in significant disparities in the
526 final emission factors.

527 Figure 9 depicts the yearly evolution of the SO₂ emissions from China's coal-fired
528 power plants from 1990 to 2010 at the unit level (only eastern China is shown on the
529 map). New power plants were constructed throughout the country after 2000.
530 Particularly, large units were rapidly constructed in the north regions, where large coal
531 mines are located, and along the eastern coastal regions, where economies are most
532 active. In addition, SO₂ emissions from large units have declined significantly since
533 2005, and many small units were terminated. Figure 10 shows NO_x emissions by unit
534 for the years 1990, 2000, 2005, and 2010. In contrast to SO₂, NO_x emissions
535 continuously increased over the entire study period given that no effective NO_x
536 emission control facilities (e.g., SCR) were operated after the generation units were
537 commissioned.

538 **3.5. Monthly Variation of Emissions**

539 Figure 11 presents the monthly profiles of power generation, CO₂ emissions, and SO₂
540 emissions from 2005–2010, which were aggregated from the monthly profiles of each
541 unit. Power generations and emissions typically peaked in December of each year due
542 to high year-end industrial activities, with the exception of 2008 during the financial
543 crisis. The second emission peak occurs in July and August, which is driven by the
544 electricity demand of air conditioners. The low point of emissions occurs in January
545 or February of each year, depending on the time of the Spring Festival.

546 As shown in Fig. 11, monthly variations in CO₂ emissions generally follows the
547 variation in power generation, whereas the monthly variation of SO₂ emissions differs
548 from that of the power generation after 2007 when FGD installations were widespread.
549 After 2007, the monthly fraction of SO₂ emissions was typically higher than the
550 fraction of power generation during the first half of the year but reversed during the
551 second half of the year, reflecting that many FGD facilities were installed by the
552 year-end to meet the government requirements of that year. In this case, the monthly
553 emission profiles developed in this study differ from previous inventories for which
554 temporal variations in power plant emissions were derived from the monthly

555 electricity generation of each province (e.g., Streets et al., 2003; Zhang et al., 2007).

556 **3.6. Data availability**

557 The early version of CPED has been integrated into the MEIC (Multi-resolution
558 Emission Inventory for China) database (both MEIC 1.0 and 1.2), which is available
559 at the following website: <http://www.meicmodel.org/>. MIEC 1.0 was incorporated to
560 the MIX Asian emission inventory (Li et al., in prep.). The most recent version of
561 CPED (documented in this work) will be incorporated to the next version of MEIC.

562 **4. Discussion**

563 **4.1. Uncertainty in Emission Estimates**

564 The uncertainty ranges of emissions estimated in this study are presented in Fig. 12.
565 The average uncertainties of emissions from coal-fired power plants in China in 2010
566 are estimated as -22% to 23% for SO₂, -15% to 15% for NO_x, -31% to 38% for
567 PM_{2.5}, -26% to 30% for PM₁₀ and -15% to 16% for CO₂. The higher uncertainty
568 range of the PM emission estimates is dominated by the uncertainties in the unabated
569 emission factors and the efficiencies of PM removal facilities. The development of a
570 local database of the actual removal efficiencies for emission control in the future will
571 help to reduce the uncertainties. The uncertainty ranges narrowed gradually from
572 1990 to 2010, representing the improved knowledge of the underlying data over time.
573 The uncertainty ranges declined from -36~38%, -24~26%, -43~55%, -32~39% and
574 -24~27% in 1990 to -22~23%, -15~15%, -31~38%, -26~30% and -15~16% in
575 2010 for SO₂, NO_x, PM_{2.5}, PM₁₀ and CO₂ respectively. As discussed in Sect. 2, many
576 of the input data in the CPED in 1990 were determined by extrapolations and
577 assumptions associated with high uncertainties, whereas the uncertainty ranges for the
578 2010 emission estimates are significantly reduced because of the extensive use of
579 unit-specific data. The unit-specific annual coal use in 2010 contributed to the
580 improved accuracy for all five species. In addition, a better understanding of sulfur
581 content and removal efficiency of FGD, coal type, ash content and heating value of
582 coal for each unit in 2010, on which the accuracy of SO₂, NO_x, PM and CO₂ emission
583 factors depend respectively, is the primary reason for the narrowed uncertainties for
584 corresponding species.

585 We further demonstrated how the emission uncertainties changed over time at the unit
586 level. For the selected generation unit (600 MW, pulverized boiler, equipped with
587 FGD, LNB, and an electrostatic precipitator), the uncertainty ranges of the emission
588 estimates for 2000 and 2010 are presented in Table 6. The uncertainty ranges for the
589 2010 estimates are significantly reduced compared with the uncertainties for 2000
590 because more unit-specific information became available in 2010. For 2010, the
591 uncertainties at the unit level are comparable with the national average, given that all
592 of the available unit-specific input data correspond to low uncertainties. However, in
593 2000, the uncertainties at the unit level are significantly higher than the national
594 average because several key parameters (e.g., annual operating hours, sulfur content
595 and heating value of coal) were derived from extrapolations and assumptions.

596 In addition, we quantified uncertainties of other potential sources by sensitivity
597 analysis. The assumption of SO₂ removal efficiencies for FGD prior to 2008 may
598 have underestimated SO₂ emissions, as some of the early installed FGD facilities were
599 not actually in operation then. Assuming 20% of FGD did not operate properly,
600 national total emissions could increase by 2%, 4% and 9% for 2005, 2006 and 2007
601 respectively. The assumption of PM_{2.5} removal efficiency for wet FGD may have
602 underestimated PM_{2.5} emissions for wet limestone-gypsum FGD. Particulate matters
603 in desulfurizers of the spray slurry from scrubbers of wet FGD are likely to exhaust
604 from stacks along with plumes. These particulate matters would offset PM_{2.5}
605 emissions absorbed by scrubbers of wet FGD (Meij and te Winkel, 2004). By
606 assuming 10% changes of PM_{2.5} emissions are induced by gypsum spray (Meij and
607 te Winkel, 2004), PM_{2.5} emissions could be increased by 0.3% in 2005 and 6.4% in
608 2010, depending on the penetrations of wet FGD. We further quantified the
609 uncertainties induced by the assumption that de-NO_x devices were not in operation
610 until 2010. By assuming that de-NO_x devices were put into operation in Beijing,
611 Shanghai and Guangdong in 2010, NO_x emission estimates could be reduced by 67
612 Gg (1% of total), indicating our assumptions have small impacts on national total NO_x
613 emission estimates. Overall, the sensitivity studies indicate that our assumptions have
614 relatively small impacts on national total emission estimates.

615 **4.2. Comparison with Previous Estimates of Emission Trends**

616 In this section, we compared our new inventory with other bottom-up emission

617 inventories, as shown in Fig. 12, in which multi-year estimates are provided (more
618 than five data points from 1990 to 2010). The discussion is focused on inventories
619 that are available for multiple species and are widely used in the community, i.e.,
620 Emission Database for Global Atmospheric Research version 4.2 (EDGAR 4.2,
621 EC-JRC/PBL, 2011) and Regional Emission inventory in Asia version 2 (REAS 2,
622 Kurokawa et al., 2013). We initially compared the CO₂ emission estimates among the
623 different emission inventories. Our estimate is consistent with Guan et al. (2012) but
624 is approximately 16%–25% lower than the estimates by three other studies (EDGAR
625 4.2, REAS 2, and Y. Zhao et al. (2013)). Our estimates are similar to those of Guan et
626 al. (2012) because both estimates used a lower coal heating value (an average of ~20
627 kJ/g) derived from energy statistics, which was approximately 20% lower than the
628 IPCC's recommended value (25.8 kJ/g) used in other studies. The lower estimate in
629 this study compared with EDGAR 4.2 might also be because the public electricity and
630 heat production sector in EDGAR 4.2 include emissions from heating plants.

631 For SO₂ emissions, EDGAR 4.2 and the official estimates by the MEP (China
632 Statistical Yearbook, NBS, 1997–2011) exceed the boundary of the 95% CI calculated
633 in this study. EDGAR 4.2 estimated a positive trend until 2008, which differs from
634 other studies, likely because EDGAR 4.2 failed to characterize the SO₂ emission
635 control progress in China's power plants after 2005. Three other inventories (REAS 2,
636 Lu et al., 2011, and this study) provided consistent trajectories for SO₂ emissions and
637 are higher than the official estimates for the period of 1998 to 2008, likely due to
638 underreported emissions by the MEP. All of the studies presented a similar growth
639 trend for NO_x emissions over the last two decades, whereas EDGAR 4.2 and REAS 2
640 are slightly higher than the upper bound of the 95% CI calculated in this study. By
641 revisiting the local emission factor measurements (Table 1), our new estimates for
642 NO_x emissions are 15%–24% lower than previous estimates (Zhang et al., 2007) for
643 the period of 1995–2004. REAS 2 used emission factors from Zhang et al. (2007) and
644 then derived higher emissions than those in this study (Kurokawa et al., 2013). REAS
645 2 concluded that NO_x emissions from China's power plants increased by 136% from

646 2000 to 2008, higher than the value of 125% of growth estimated in this study during
647 the same period due to different assumptions in the evolution of combustion
648 technologies. The **PM** emission trends presented in this study generally agree well
649 with previous studies (Lei et al., 2011; Y. Zhao et al., 2013) but significantly differ
650 from REAS 2. REAS 2 presented a 36% increase in PM_{2.5} emissions from 2005 to
651 2008, whereas we estimated a 24% decrease during the same period, most likely due
652 to different assumptions regarding the penetration of PM_{2.5} removal devices.

653 **4.3. Comparison with the CARMA Database**

654 The CARMA database (Wheeler and Ummel, 2008; Ummel, 2012) has been widely
655 used to allocate power plant emissions in different global and regional emission
656 inventories (e.g., EDGAR 4.2 and REAS 2). In this section, we compared the
657 magnitude and spatial distribution of CO₂ emissions between this study and the
658 CARMA database throughout China for 2009. The total magnitude of CO₂ emissions
659 for the two inventories is comparable, with a large discrepancy in the numbers of
660 power plants. In this study, we estimated 2.51 Pg CO₂ emissions from 2320 power
661 plants, whereas CARMA estimated 2.47 Pg CO₂ emissions from 945 plants.

662 Figures 13a and b show the spatial distributions of CO₂ emissions for CPED and the
663 CARMA database, which illustrate that CARMA neglects many small power plants.
664 Figure 13c depicts the cumulative curves of the power plant numbers sorted by CO₂
665 emissions from low to high. In this study, power plants with annual CO₂ emissions
666 less than 1 Tg accounted for 76% of the total plants, whereas the share of these plants
667 was only 44% in CARMA. In summary, CARMA omitted ~1300 small power plants
668 throughout China (annual CO₂ emissions less than 1 Tg) in 2009. In addition, for
669 power plants consisting of several generating units, CARMA may omit information
670 on partial units. For example, the Tuoketuo Power Plant located in Inner Mongolia is
671 composed of 10 generating units with a total capacity of 5400 MW. Its CO₂ emission
672 estimated by CARMA is 15.1 Tg, which is only 56% of the value estimated in this
673 study, indicating CARMA's significant underestimation of coal consumption for the

674 plant, which is most likely caused by missing information on some units.

675 Another major difference between the two inventories is the emission locations from
676 the power plants. Figure 13d shows a magnified comparison of the spatial
677 distributions of CO₂ emissions between the two inventories over the southwest region
678 of China, which illustrates the plant-specific emissions and locations. The power plant
679 locations in CARMA deviate from those in our inventory due to the different
680 geographical allocation methods used in the two datasets. In this study, the location of
681 each power plant was obtained from the MEP database and was manually verified
682 using Google Earth, which allowed for a high accuracy in the geographical
683 distribution of emissions. CARMA generally treats the city-center latitudes and
684 longitudes as the approximate coordinates of the power plants in China (Wheeler and
685 Ummel, 2008). Ummel (2012) reported that the precise coordinates are only available
686 for 10% of the plants worldwide in CARMA, and the reported emissions are within
687 20% of the actual values for only 75% of plants. For 46 power plants included in both
688 CARMA and in CPED over the southwest region, the average distance between the
689 locations reported in CARMA and in CPED is approximately 50 km, indicating that
690 the CARMA database may be insufficient to support air quality modeling on regional
691 and urban scales.

692 Figure 14 further presents the relative differences in the CO₂ emission flux (g/m²) at
693 various spatial resolutions (0.1°, 0.5°, 1°, and 2°) in 2009 for the two datasets. The
694 degree of differences between the two datasets is highly correlated to the spatial
695 resolution. The differences are diminished as the spatial resolution decreases. The
696 average differences between the two datasets are within 10% at a 2° resolution and
697 20–30% at a 1° resolution, indicating that CARMA has an acceptable accuracy to
698 support modeling studies at the global scale. However, at a 0.1° resolution, the
699 relative differences between the two inventories are as high as 70%, suggesting that
700 CARMA is not appropriate for high-resolution modeling.

701

702 5. Concluding Remarks

703 This is the first study to develop a unit-based inventory of technologies, activities, and
704 emissions for China's coal-fired power plants for the period of 1990–2010. The CPED
705 database developed in this study includes ~5700 in-use electricity generating units in
706 2010 and ~1900 retired units since 2005. From the high-resolution CPED database,
707 spatial and temporal variations of China's power plant emissions were presented from
708 1990 to 2010. In 2010, SO₂, NO_x, PM_{2.5}, PM₁₀ and CO₂ emissions from China's
709 coal-fired power plants are estimated to be 7.7 Tg, 8.3 Tg, 0.83 Tg, 1.32 Tg and 2.8
710 Pg respectively. From 1990 to 2010, SO₂, NO_x, and CO₂ emissions from power plants
711 increased by 56%, 335%, and 442%, respectively, and PM_{2.5} and PM₁₀ emissions
712 decreased by 23% and 27% respectively during the same period. Energy efficiency of
713 coal-fired power plants in China has been improved by approximately 20% in 20
714 years owing to measures imposed by the Chinese government to encourage
715 large-scale power units and to decommission small units.

716 The most significant changes in power plant emissions occurred during 2005–2010,
717 driven by the dramatic economy growth and offset by the strengthened emission
718 control measures. Large units were rapidly constructed in the north regions and
719 eastern coastal regions to meet the high electricity demand, while growth trend of
720 emissions has been effectively curbed since 2005 by installation of FGD and the
721 optimization of the generation fleet mix. 84% of the total unit capacities were
722 equipped with FGD in 2010, which helped reducing SO₂ emissions to half of the 2006
723 emission level. The increasing penetration of advanced LNB after 2006 has reduced
724 the average NO_x emission factor by 16%, but still did not constrain the growth of NO_x
725 emissions. New environmental regulations, including the phase-out of small units
726 with inefficient PM emission control facilities, the widespread use of electrostatic
727 precipitators and bag filters, and FGD installations that has a co-benefit to PM
728 removal, have led to the 40% decrease of PM_{2.5} emissions from 2005 to 2010.

729 Great emission reduction potentials from coal-fired power plants are expected in the
730 near future by implementation of new policies including promotion of ultra-low
731 emission units, decommission of flue gas bypass system, and strengthening
732 supervision and management, etc. The removal efficiencies of existing FGD and
733 de-NO_x devices are expected to be improved with decommission of flue gas bypass
734 system. More efficient emission control technologies are expected to continuously

735 come into the marketplace, with the implementation of the government plan (NDRC,
736 2014) which requires reducing emissions from coal-fired plants down to the level of
737 gas-fired plants.

738 The new inventory developed in this work has several advantages against previous
739 studies. First, to our best knowledge, it is the most complete coal-fired power plant
740 database for China with inclusion of more than 7657 in-use and retired units, enabling
741 more accurate emission estimates at unit level. Second, CPED has dynamic
742 information for a given unit including commission/decommission time of units,
743 changes in technologies, and operating condition of emission control facilities. The
744 above information further improved the accuracy of emission estimates for every time
745 step. Third, exact locations of each unit were obtained from MEP and crosschecked
746 by Google Earth manually, which could benefit to chemical transport modelling at
747 high spatial resolution. The improved accuracy of CPED has been validated by
748 another recent study using satellite-recorded tropospheric NO₂ columns around the
749 power plants (Liu et al., 2015).

750 Although we believe that the accuracy of CPED has been substantially improved, it
751 still has some uncertainties. Emission estimates for 1990s are thought to be more
752 uncertain than 2000s because a few parameters during 1990s were determined by
753 extrapolations and assumptions rather than using unit-specific data. Units retired
754 before 2005 were not included in our database. However, we believe that omitting
755 those units would have minor impacts to the accuracy of CPED as large scale
756 retirement of coal-fired power plants were only occurred after 2005. Local
757 measurements for PM emission factors are still rare compared to SO₂ and NO_x,
758 leading to higher uncertainties in PM emission estimates. In recent years, continuous
759 emission monitoring systems (CEMS) were gradually equipped in electricity
760 generating units, offering the opportunities of using real-time emission data. Applying
761 CEMS data in the future will further improve the accuracy of emission estimates in
762 CPED.

763 Acknowledgments

764 This study was supported by China's National Basic Research Program
765 (2014CB441301) the National Natural Science Foundation of China (41222036,
766 41275026, and 71322304), and the EU FP-7 program MarcoPolo. Q. Zhang and K. B.

767 He are supported by the Collaborative Innovation Center for Regional Environmental
768 Quality. We would express special thanks to C. H. Chen, G. N. Geng, C. P. Hong, S. C.
769 Kang, and S. W. Wang for crosschecking the locations of power plants.

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972 Table 1. Summary of NO_x emission factors for different types of coal-fired power plants

Unit Size	Combustion Technology	Bituminous Coal, g/kg ^a	Average Emission Factor, g/kg ^a	Anthracite Coal, g/kg ^a	Average Emission Factor, g/kg ^a
Large (≥300 MW)	Advanced LNB ^b	2.88 ¹ ,3.05 ² ,3.28 ³ ,3.55 ⁴ ,4.13 ⁵ , 4.17 ⁶ ,4.64 ⁷	4.06	6.14 ⁷ ,6.58 ⁴ ,6.99 ⁸	6.50
	Traditional LNB	4.40 ⁹ ,4.98 ¹⁰ ,5.23 ¹¹ ,5.06 ¹² , 5.65 ⁸ , 7.78 ⁴	5.08	4.61 ¹¹ ,4.99 ¹² ,7.77 ⁷ ,7.94 ⁸ ,8.05 ¹⁰ ,8.73 ⁹	8.04
Medium (≥100 MW and <300 MW)	Traditional LNB	4.34 ¹⁰ ,5.52 ¹¹ ,6.97 ¹³	6.78	7.07 ¹¹ ,7.56 ¹⁰	7.29
	Non-LNB	5.46 ¹⁴ ,8.12 ¹¹	7.63	8.25 ¹⁰ ,12.11 ¹¹	10.46
Small (<100 MW)	Non-LNB	6.55 ¹⁵ ,6.88 ¹¹	6.66	10.01 ¹⁵ ,11.50 ¹¹	10.50

^aSample weighted mean

^bLNB: Low-NO_x Burners

Data sources: ¹Qian,2010, ²Cao and Liu,2011, ³Zhu,2009, ⁴Wang et al.,2008, ⁵Yi et al.,2006, ⁶Zhu et al.,2009, ⁷Xie et al.,2008, ⁸Wang et al.,2007, ⁹Bi and Chen,2004, ¹⁰Tian,2003, ¹¹Zhu, 2011, ¹²Zhu, et al.,2004, ¹³Feng and Yan,2007, ¹⁴Zhao et al., 2010, ¹⁵Zhao et al., 2008

973 Table 2. Summary of the mass fractions of particulate matter of different size fractions
974 to the total particulate matter in fly ash for different types of boilers ^a; values are given
975 as percentages (%)

Size Fraction	Boiler Type		
	Pulverized Boilers	Circulating Fluidized Beds	Grate Furnaces
PM _{>10}	77	71	63
PM _{2.5-10}	17	22	23
PM _{2.5}	6	7	14

976 ^aData sources: Klimont et al. (2002) and Zhao et al. (2010).

977

978

979 Table 3. Removal efficiencies of different control technologies for SO₂ and particulate
980 matters; values are given as percentages (%)

Technology	SO ₂	PM _{2.5}	PM _{2.5-10}	PM _{>10}
Cyclones		10	70	90
Wet scrubbers	20	50	90	99
Electrostatic Precipitators		93	98	99.5
FGD ^a	78 ^b	50	90	99
Bag Filters		99	99.5	99.9

^aFGD: Flue-gas Desulfurization

^bTime dependent parameter, 78% is the coal-consumption weighted mean efficiency in 2010.

981 Table 4. Capacity sizes, technology penetrations, fuel qualities, emission factors and emissions of coal-fired power plants in China from 1990 to
 982 2010

Category	Subcategory	1990	1995	2000	2005	2006	2007	2008	2009	2010
Capacity Size ^a	<100 MW	39.3%	34.0%	29.1%	25.5%	23.1%	19.1%	15.3%	13.1%	11.5%
	[100,300) MW	48.7%	44.0%	35.7%	31.1%	29.1%	26.7%	23.9%	21.4%	18.7%
	[300,600) MW	10.9%	19.9%	30.1%	33.4%	34.0%	33.2%	33.3%	34.3%	35.4%
	≥600 MW	1.2%	2.2%	5.0%	9.9%	13.8%	21.0%	27.5%	31.2%	34.4%
Technology Penetration ^a	Traditional LNB	12.0%	22.1%	38.7%	53.7%	51.8%	46.6%	44.2%	42.1%	39.4%
	Advanced LNB	0.0%	0.0%	0.0%	0.0%	7.4%	19.8%	29.2%	35.9%	42.0%
	FGD	0.1%	1.0%	2.1%	12.2%	29.5%	49.9%	70.2%	81.9%	85.6%
	Cyclones	7.6%	7.4%	5.2%	3.6%	3.0%	2.3%	1.6%	0.7%	0.3%
	Wet Scrubbers	46.3%	40.4%	19.0%	6.9%	6.1%	5.0%	3.9%	3.1%	2.5%
	Electrostatic Precipitators	44.3%	49.8%	72.5%	86.1%	87.5%	89.1%	90.8%	92.0%	92.8%
	Bag Filters	1.7%	2.3%	3.3%	3.4%	3.4%	3.5%	3.7%	4.2%	4.4%
Fuel Quality	Heating Value (kJ/g-coal)	20.1	20.2	21.0	19.0	19.3	20.0	19.3	18.9	18.8
	Coal Consumption Rate (gce/kWh)	406.7	389.0	374.3	356.4	351.8	343.5	335.3	330.5	327.1
	Sulfur Content (%)	1.07	1.12	1.10	1.04	1.03	1.00	0.97	0.95	0.95
Emission Factor	SO ₂ (g/kWh)	10.73	9.82	9.15	8.69	7.47	5.34	4.06	3.00	2.48
	NO _x (g/kWh)	4.14	3.82	3.37	3.41	3.23	2.92	2.84	2.78	2.67
	PM _{2.5} (g/kWh)	2.34	1.84	1.12	0.73	0.62	0.48	0.39	0.31	0.27
	PM ₁₀ (g/kWh)	3.89	3.11	1.92	1.29	1.09	0.83	0.66	0.50	0.42
	CO ₂ (g/kWh)	1126.1	1077.1	1036.5	986.9	974.1	951.2	928.4	915.1	905.6
	SO ₂ (g/kg-coal)	18.12	17.42	17.52	15.85	14.03	10.62	7.98	5.84	4.89

	NO _x (g/kg-coal)	7.00	6.78	6.46	6.23	6.07	5.81	5.58	5.41	5.26
	PM _{2.5} (g/kg-coal)	3.95	3.26	2.14	1.33	1.17	0.96	0.77	0.61	0.53
	PM₁₀ (g/kg-coal)	6.58	5.51	3.67	2.35	2.05	1.66	1.29	0.97	0.83
	CO ₂ (g/kg-coal)	1902.9	1910.8	1984.8	1801.2	1828.1	1890.6	1822.9	1784.3	1781.9
	SO ₂ (Tg/year)	4.94	7.74	9.27	16.70	16.73	14.15	10.96	8.22	7.71
	NO _x (Tg/year)	1.91	3.01	3.42	6.56	7.24	7.75	7.67	7.62	8.29
Emissions	PM _{2.5} (Tg/year)	1.08	1.45	1.13	1.40	1.39	1.28	1.06	0.85	0.83
	PM₁₀ (Tg/year)	1.79	2.45	1.94	2.48	2.44	2.21	1.77	1.37	1.32
	CO ₂ (Pg/year)	0.52	0.85	1.05	1.90	2.18	2.52	2.51	2.51	2.81

^aShares of coal consumption for each capacity size/technology

983 Table 5 Capacity sizes, technology penetrations, and emission factors of coal-fired power plants in China's six interprovincial power grids in
 984 2005 and 2010

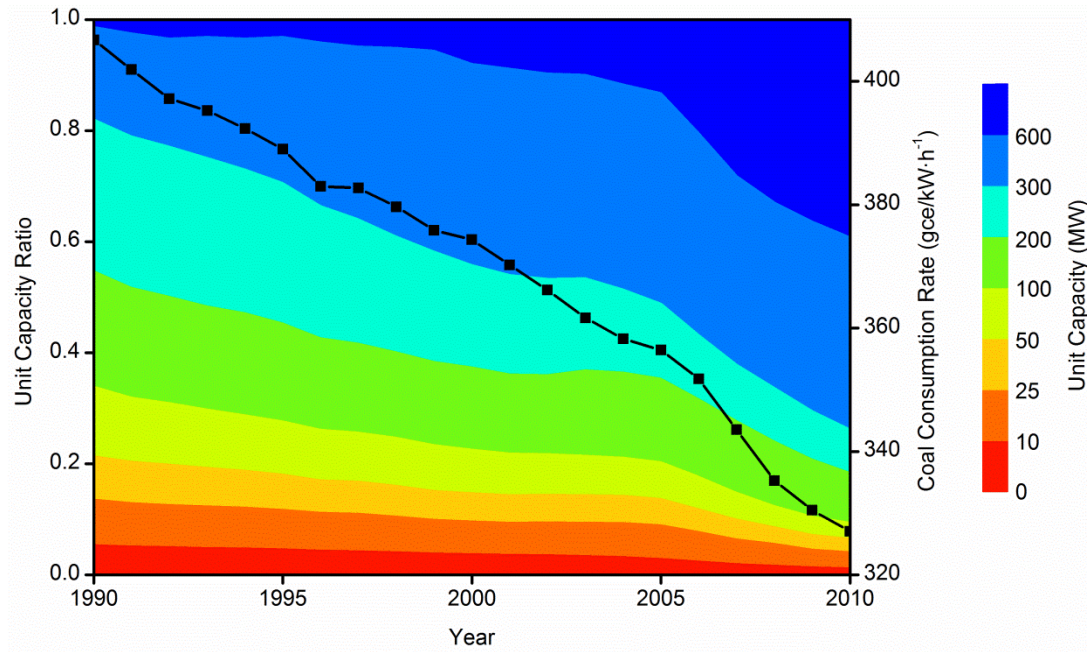
Year	Grid	Capacity Size (MW) ^a				Technology Penetration ^a			Sulfur Content (%)	Emission Factor (g/kWh)				
		(0,100]	[100,300)	[300,600)	≥600	FGD	LNB	ESP		SO ₂	NO _x	PM _{2.5}	PM ₁₀	CO ₂
2005	North	20.0%	29.6%	36.4%	14.0%	14.5%	62.6%	89.1%	1.05	8.74	3.36	0.66	1.20	954.6
	Northeast	23.9%	41.2%	24.5%	10.4%	2.1%	43.7%	79.6%	0.41	4.01	3.99	1.18	2.01	1094.0
	East	17.6%	18.4%	39.7%	24.3%	27.1%	70.5%	92.2%	0.74	5.28	2.96	0.45	0.78	958.9
	Central	22.3%	30.6%	45.0%	2.1%	9.5%	57.6%	87.1%	1.45	12.56	3.76	0.96	1.75	971.4
	Northwest	23.3%	29.4%	40.4%	6.9%	0.2%	59.9%	92.0%	1.21	11.09	3.40	0.69	1.23	1001.5
	South	18.4%	30.7%	39.1%	11.8%	18.3%	66.9%	88.6%	1.45	12.66	3.52	0.74	1.28	1038.2
2010	North	11.1%	21.4%	38.4%	29.2%	88.0%	81.4%	91.0%	1.00	2.45	2.79	0.26	0.41	914.7
	Northeast	12.9%	24.5%	31.1%	31.5%	60.1%	73.6%	89.0%	0.51	2.23	3.32	0.55	0.88	1042.9
	East	10.0%	7.1%	25.7%	57.2%	94.3%	87.2%	96.2%	0.69	1.26	2.28	0.16	0.25	877.3
	Central	6.2%	17.5%	36.1%	40.2%	78.7%	86.6%	92.6%	1.18	3.27	2.73	0.34	0.55	821.7
	Northwest	10.1%	20.2%	39.8%	29.9%	77.0%	83.8%	95.7%	0.98	3.44	2.78	0.27	0.43	956.7
	South	4.4%	14.4%	39.8%	41.4%	92.7%	91.4%	98.0%	1.32	3.41	2.56	0.20	0.31	904.4

985 ^aShares of coal consumption for each capacity size/technology

986 Table 6 Uncertainty ranges of emission estimates for a large coal-fired generation unit
 987 (600 MW, pulverized boiler, equipped with FGD, LNB, and an electrostatic
 988 precipitator) in China; the values represent the 95% CI around the mean

Species	Year	
	2000	2010
SO ₂	-58%~56%	-21%~14%
NO _x	-100%~179%	-28%~47%
PM _{2.5}	-61%~95%	-38%~49%
PM ₁₀	-81%~112%	-39%~44%
CO ₂	-28%~33%	-16%~18%

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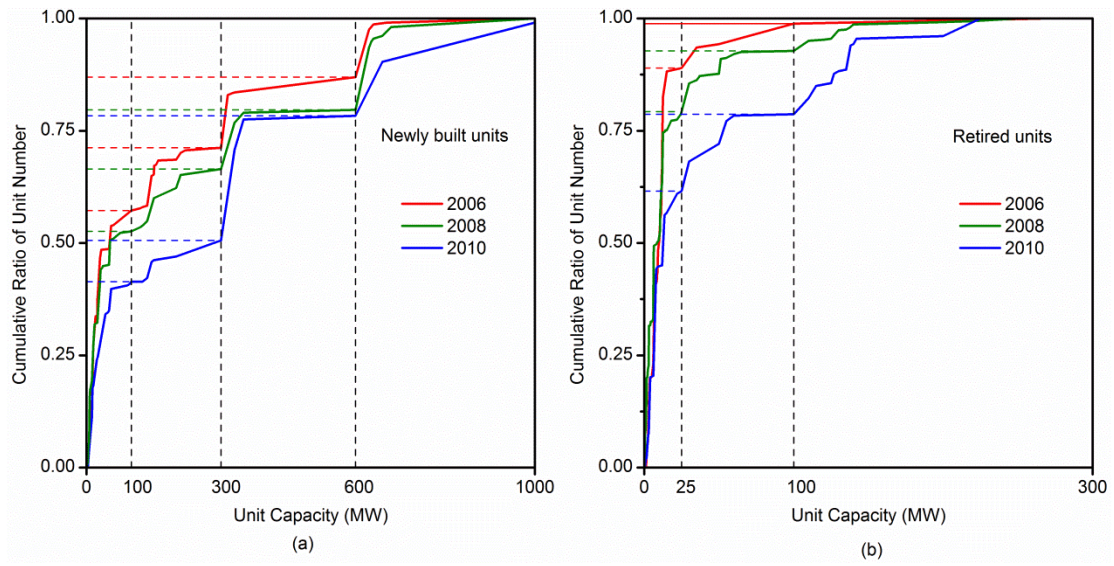
991

992 Figure 1. Trends in generation mix by capacity and the average coal consumption

993 rates (black line) during 1990-2010.

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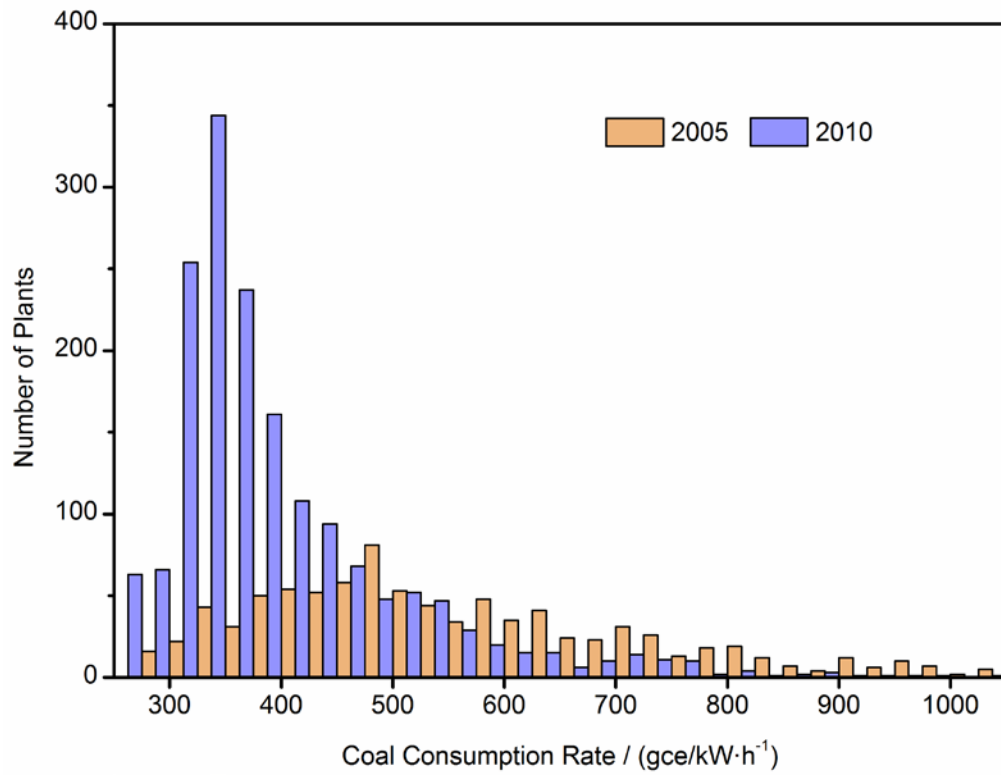
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998 Figure 2. Cumulative ratio of unit number for (a) newly constructed and (b) retired
999 electric generating units for 2006, 2008 and 2010. The units are sorted according to
1000 ascending capacity along the x-axis.

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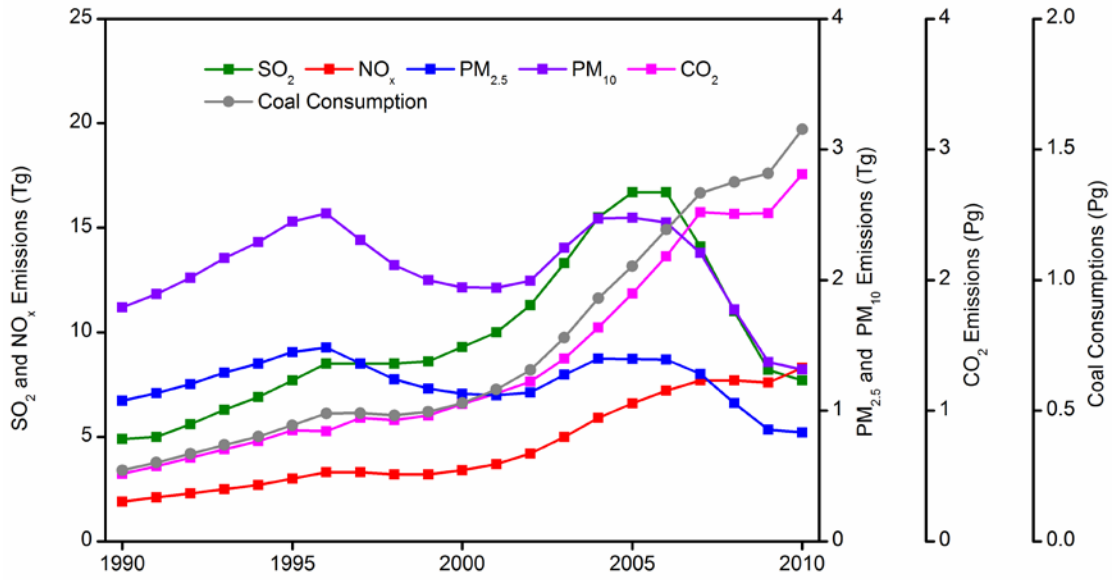
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1005 Figure 3. Distribution of coal consumption rates in coal-fired power plants in 2005

1006 and 2010.

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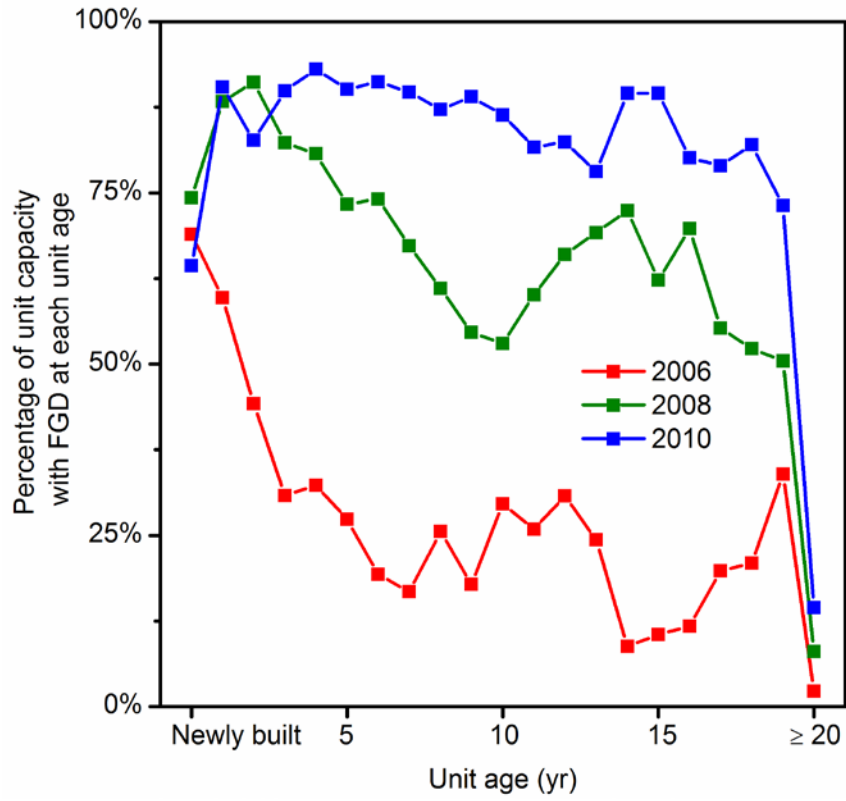


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1011 Figure 4. Coal consumptions and emissions of SO₂, NO_x, PM_{2.5}, PM₁₀ and CO₂ of
1012 coal-fired power plants in China from 1990 to 2010.

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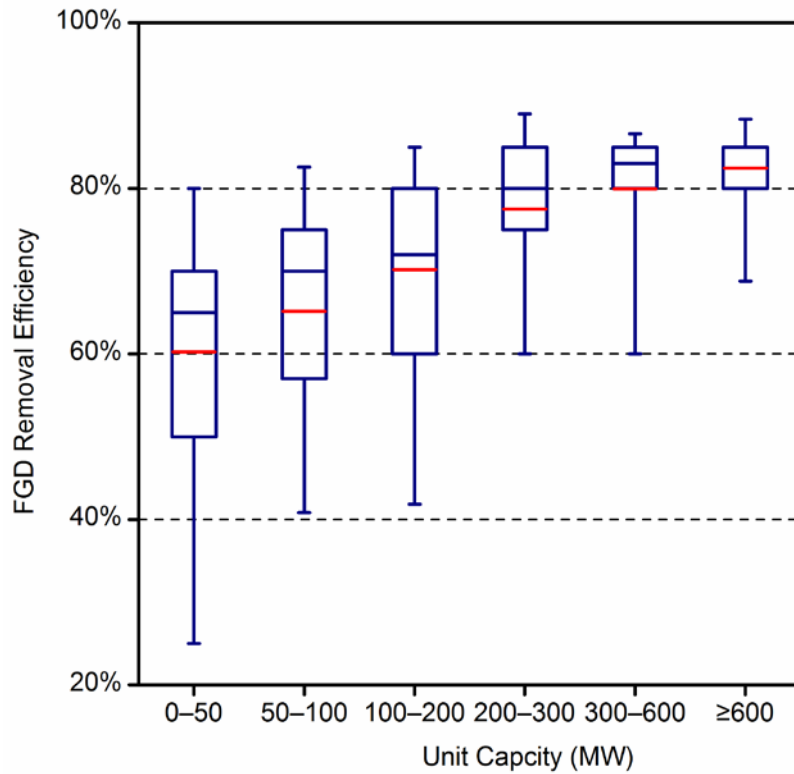


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1016 Figure 5. Distributions of FGD penetration for electric generating units of various
 1017 ages in 2006, 2008 and 2010.

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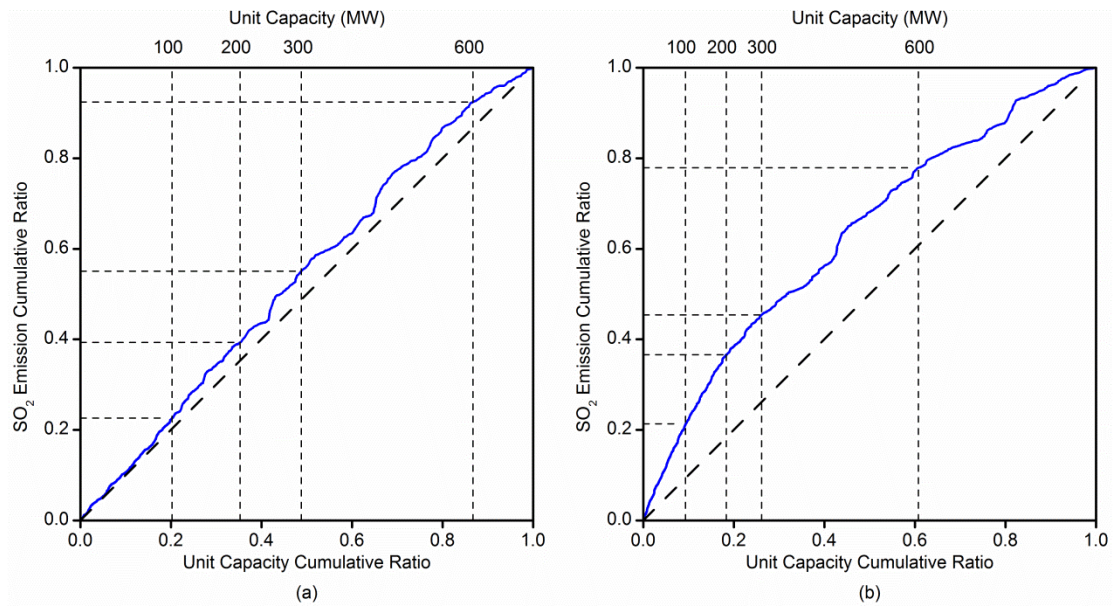
1020

1021 Figure 6. FGD removal efficiencies for electric generating units of various sizes in
 1022 China in 2010. The blue horizontal line represents the median of the removal
 1023 efficiencies, the red horizontal line represents the mean removal efficiencies, the box
 1024 denotes the 25% and 75% percentiles, and the whiskers denote the 5% and 95%
 1025 percentiles.

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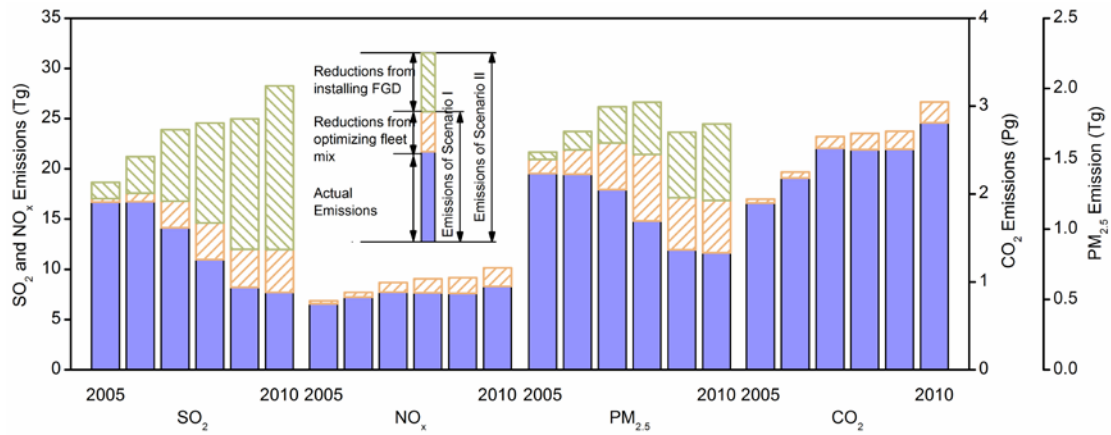
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1031 Figure 7. Cumulative ratio of SO₂ emissions by unit capacity for the years (a) 2005
1032 and (b) 2010. The units are sorted according to ascending capacity along the x-axis.

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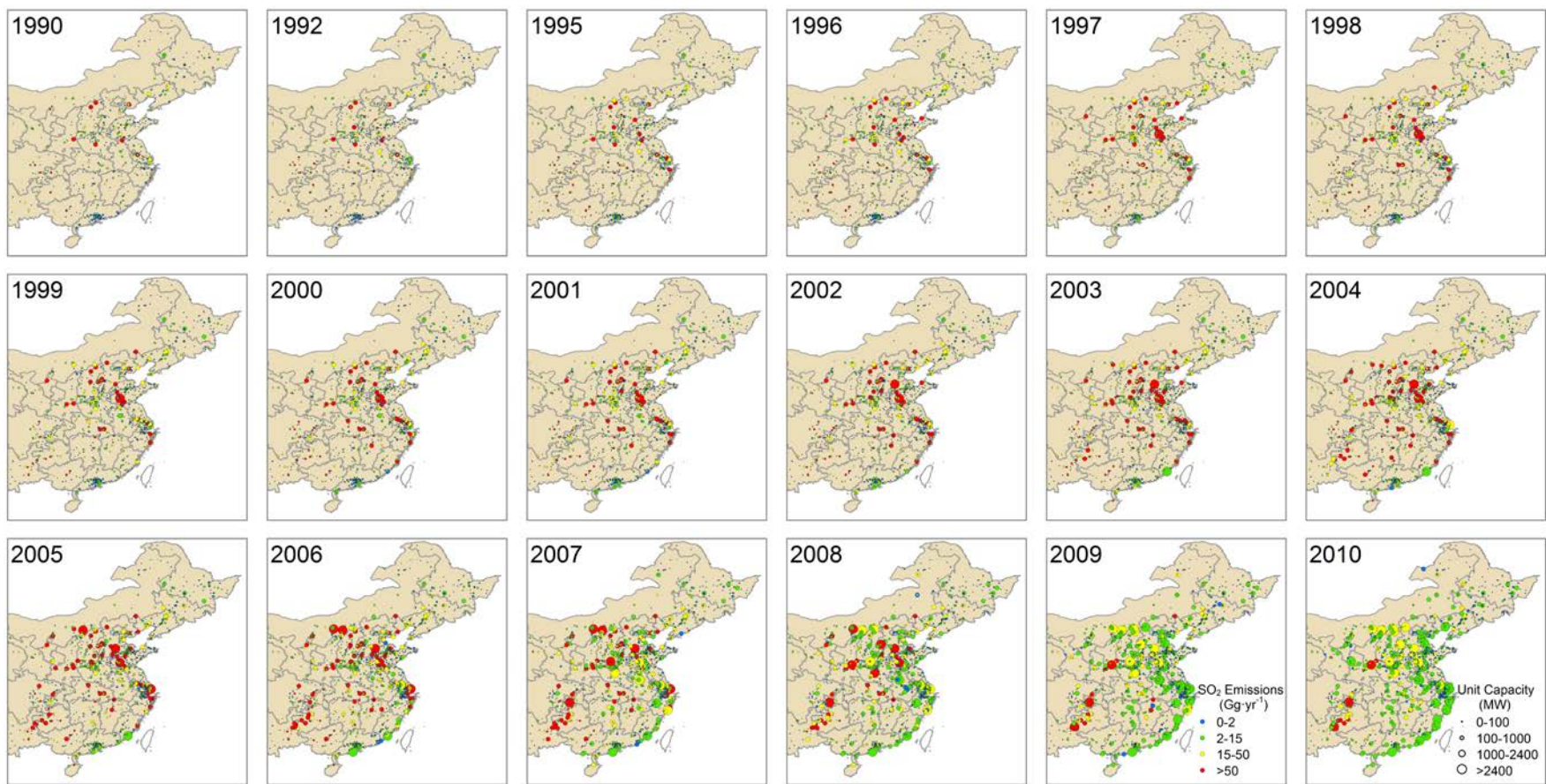


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1037 Figure 8. Reductions in SO₂, NO_x, PM_{2.5} and CO₂ emissions from major emission
1038 control measures during the 11th five-year period (2005–2010). The solid blue bar
1039 denotes our estimates of inter-annual power plant emissions. The green and yellow
1040 bars illustrate the reduction in emissions due to FGD installations and optimization of
1041 the generation unit fleet mix, respectively.

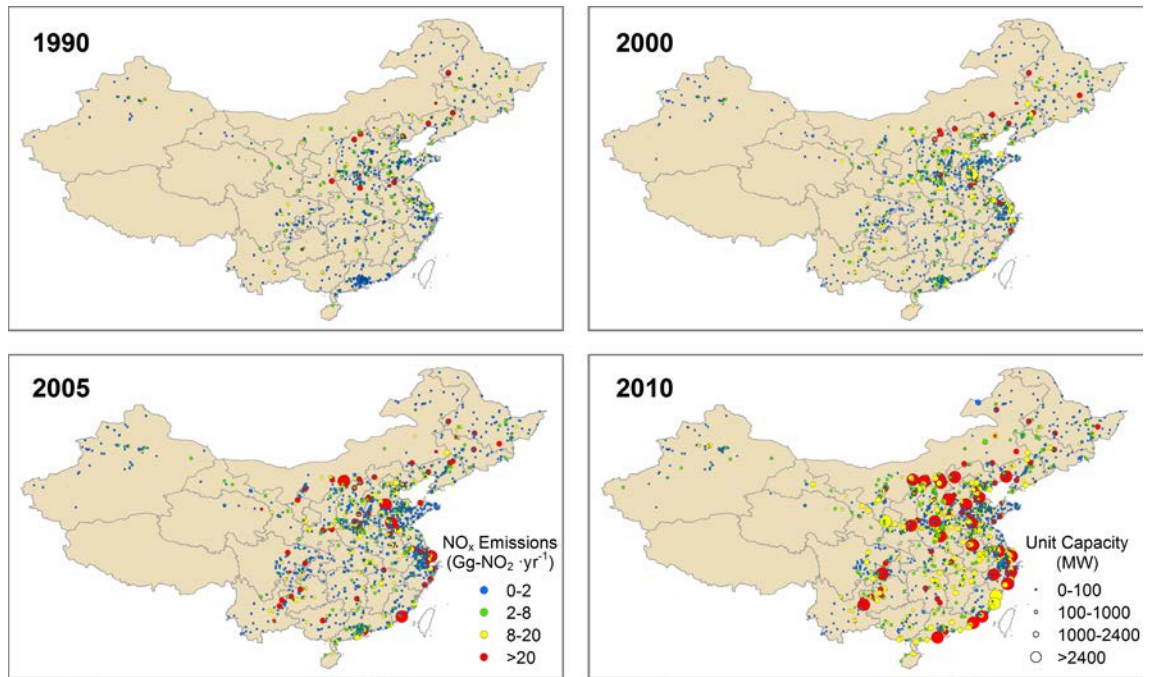
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1044 Figure 9. Evolution of SO₂ emissions from coal-fired power plants in China, 1990-2010. Units: Gg·yr⁻¹.

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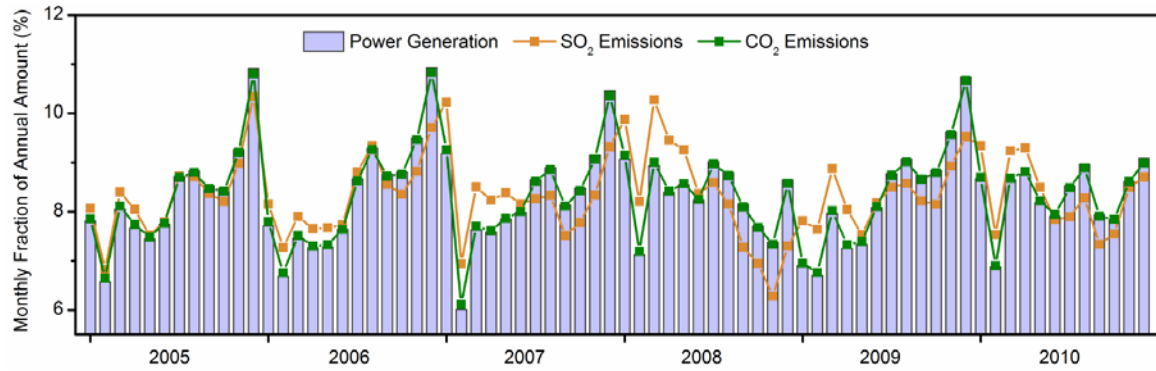


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1047 Figure 10. Spatial distribution of NO_x emissions from China's coal-fired power plants

1048 in 1990, 2000, 2005 and 2010. Units: Gg-NO₂·yr⁻¹.

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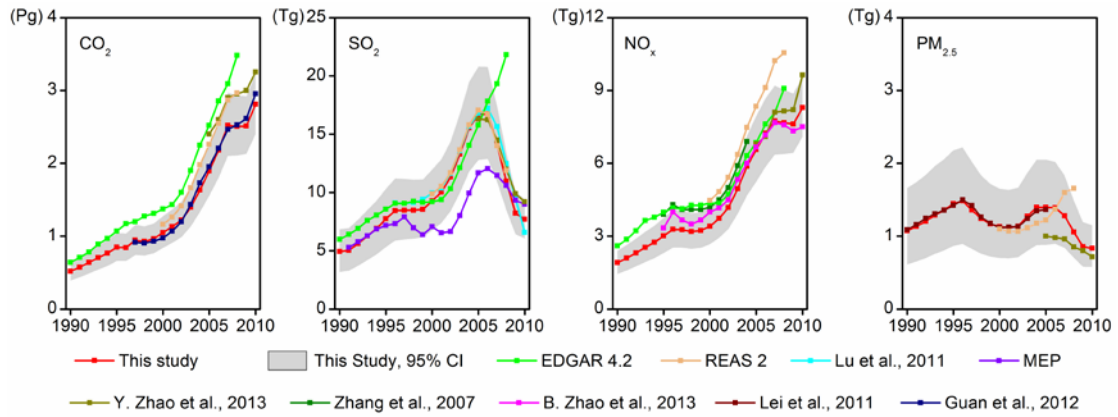


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1052 Figure 11. Monthly profiles of thermal power generation and coal-fired power plant
 1053 SO₂ and CO₂ emissions in China. The y-axis values represent the fraction of the
 1054 monthly emissions to annual emissions.

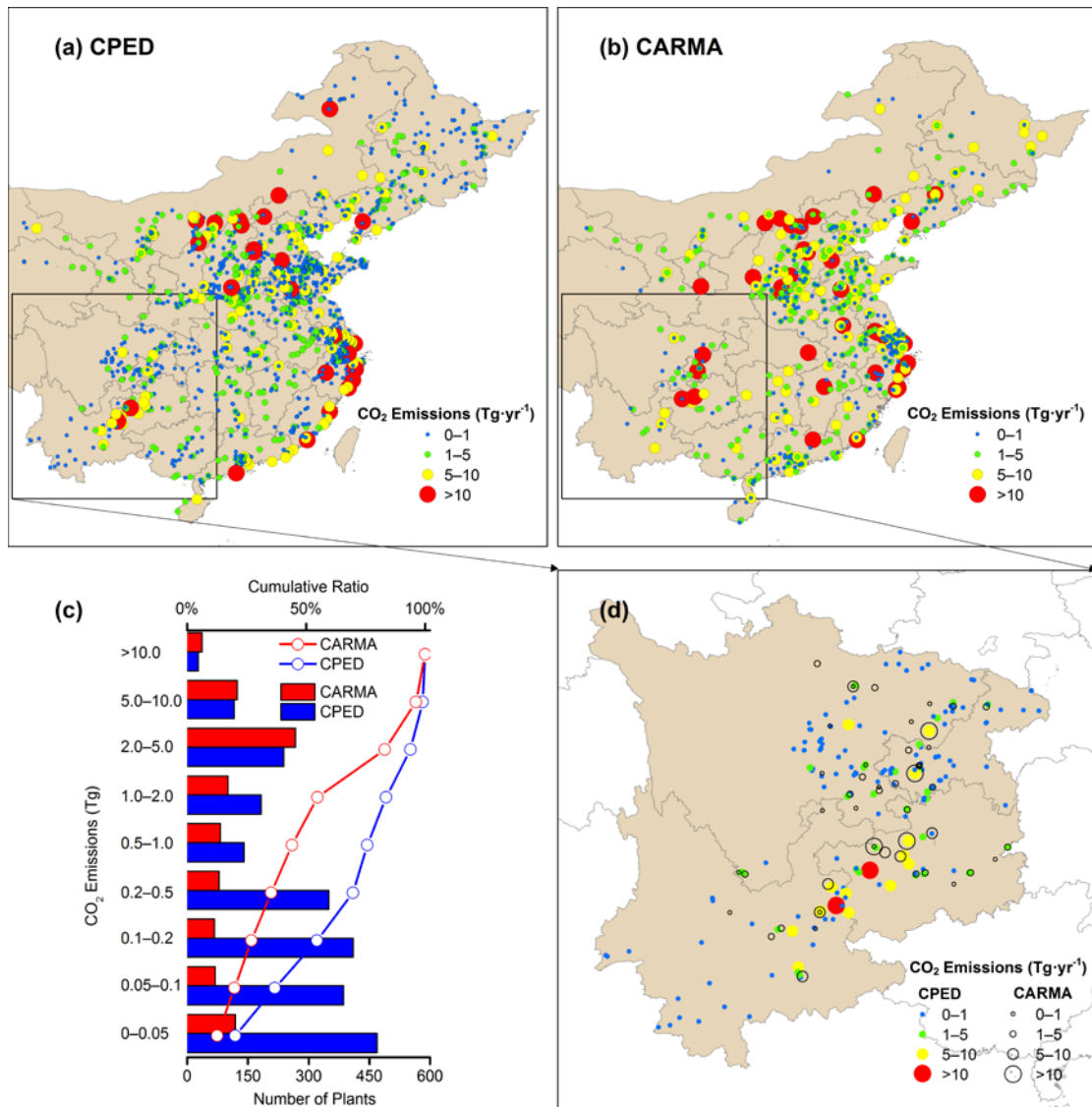
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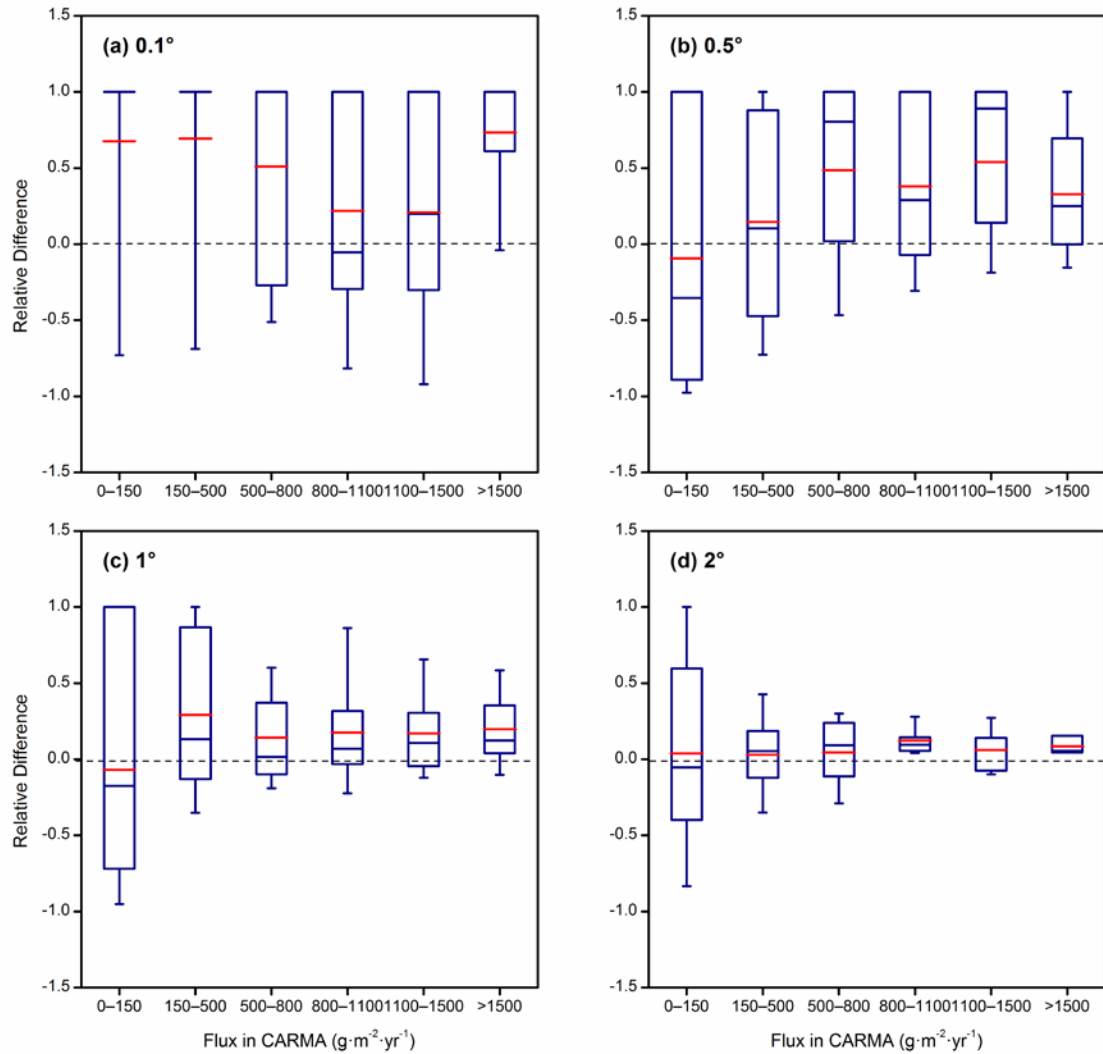
1058 Figure 12. Comparisons of SO₂, NO_x, PM_{2.5} and CO₂ emissions from China's
1059 coal-fired power plants during 1990 and 2010.



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1062 Figure 13. (a) Spatial distribution of CO₂ emissions in CPED in 2009. (b) Spatial
 1063 distribution of CO₂ emissions in CARMA in 2009. (c) Comparisons of CO₂ emissions
 1064 between CARMA and CPED by plant numbers in 2009. The plants are sorted
 1065 according to ascending CO₂ emissions along the y-axis. The red and blue lines denote
 1066 the plant number cumulative ratio for CARMA and CPED, respectively. (d)
 1067 Comparisons of the spatial distribution of CO₂ emissions in southwest China between
 1068 CARMA and CPED in 2009.



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1071 Figure 14. Comparisons of CO₂ emissions between CARMA and CPED for various
 1072 spatial resolutions (from 0.1° to 2°) in 2009. The box plots show the binned relative
 1073 differences $(a-b)/(a+b)$, where a is the CARMA estimate, and b is the CPED estimate.
 1074 The blue horizontal line is the median of the relative differences, the red horizontal
 1075 line is the mean of the relative differences, the box denotes the 25% and 75%
 1076 percentiles, and the whiskers denote the 10% and 90% percentiles. A perfect
 1077 agreement would correspond to a median and mean equal to zero.