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China's CO_2 emissions estimated from the bottom up: Recent trends, spatial distributions, and quantification of uncertainties

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HIGHLIGHTS

► A database of CO_2 emission factors specific to China is established by sector.
► China's CO_2 emissions are estimated based on a bottom-up method for 2005–2009.
► The uncertainty of China's CO_2 emissions is quantified with Monte-Carlo simulation.
► Improved energy efficiency slows the increase of CO_2 emissions for certain sectors.

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ABSTRACT

China's emissions of anthropogenic CO_2 are estimated using a bottom-up emission inventory framework based on a detailed categorization of economic sectors and provincial economic and energy data. It includes a newly compiled database of CO_2 emission factors employing the latest field study results from China. Total annual emissions are estimated to have risen from 7126 to 9370 Mt CO_2 from 2005 to 2009. Recent policies to conserve energy and reduce emissions have been effective in limiting CO_2 emissions from power and iron & steel plants, but have had little effect on those from cement production. The uncertainties of China's CO_2 emissions are quantified for the first time using Monte-Carlo simulation, producing a 95% confidence interval (CI) of −9% to +11% for total emissions in 2005. The largest contributors to sector-level emission uncertainty are emission factors for most industrial sources and activity levels for power plants, transportation, and residential & commercial sources. Application of province-level energy consumption and China-specific emission factors in some sectors results in higher annual emission estimates for 2005-2008 as compared with other studies, although most of those are within the 95% CIs of this study.

1. Introduction

Fossil energy combustion and industrial processes are the most important anthropogenic sources of the greenhouse gas carbon dioxide (CO_2). From 2000 to 2009, China's coal-dominated energy consumption increased at an annual rate of 9%, driven by swift economic development (NBS, 2010a). China accordingly surpassed the U.S. in 2006 to become the largest national source of CO_2 emissions, disregarding uncertainties.

While China's leading share of global CO_2 emissions is recognized, previous studies mainly estimated its emissions at the national level and in broad energy categories (CDIAC, 2010; PBL, 2010; USEIA, 2010). Detailed analysis by region and sector, which is important for both scientific research and design of emission control policies, has been lacking. Higher spatial resolution of emissions, for instance, supports use of chemical transport models to investigate the carbon cycle and to assess the co-benefits of carbon controls on regional and local air quality. Finer categories of emission sources can help policy makers better prioritize emission controls. Although the U.S. Carbon Dioxide Information Analysis Center (CDIAC) has estimated provincial emissions, these were generated not by bottom-up methods but by allocating the national total to provinces according to provincial fractions of total energy consumption.

Moreover, the uncertainties of China's CO_2 emissions are poorly quantified. Clear discrepancies exist between published estimates from different international sources (CDIAC, 2010; PBL, 2010; USEIA, 2010). Inconsistencies or errors in Chinese energy statistics

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have been invoked to approximate uncertainties of CO_2 emissions (Streets et al., 2001; Gregg et al., 2008). Another source of uncertainty is the reliance on global default values in emission estimation, including CO_2 emission factors (EF) and heating values of fuels. The Intergovernmental Panel on Climate Change (IPCC) advises application of country-specific EFs (IPCC, 2006), but as there is no previously published China-specific EF database, prior studies have had to rely on global default EFs (IPCC, 2006; USEIA, 2011). This ignores distinctive characteristics of a number of major emission processes in China.

Poorly quantified uncertainty means that the accuracy of estimates of China's world-leading CO_2 emissions is not well understood. Formal statistical analysis of China's CO_2 emission uncertainty is of self-evident value to scientific investigation of China's evolving role in the global carbon cycle. Quantification of CO_2 emission uncertainties is also crucial to policy processes designed to meet carbon control targets, the measurement and crediting of carbon reductions, and the trade of carbon allowances through domestic and international policy mechanisms. In 2009, China announced a commitment to reduce its carbon intensity (i.e., CO_2 emissions per unit GDP) by 40–45% by 2020 compared to 2005 level (Su, 2009). The ability to measure policy successes or failures at achieving such targets will depend fundamentally on the accuracy of emission estimates, nationally and at province and sector levels. For reasons of both science and policy, therefore, objective quantification of the uncertainty of China's CO_2 emissions, identification of its primary sources, and evaluation of ways to reduce it over time are both warranted and timely.

In this study, a bottom-up CO_2 emission inventory is developed for China, for the first time based on detailed provincial economic and energy data, and using a newly detailed categorization of economic sectors. A new database of CO_2 EFs for China is established, combining domestic field measurements by the authors and other researchers. Statistical methods are applied to quantify the uncertainty of these emission factors by sector and fuel. China's CO_2 emissions are then evaluated for 2005–2009 based on the new EF database, as well as two global default EF databases for comparison. The emission uncertainties and their main causes are quantitatively analyzed by sector, for the first time, using Monte-Carlo simulations.

2. Methods

Chinese CO_2 emissions are calculated as the product of activity levels (AL, either energy consumption or industrial production) and EFs (expressed as the mass of emitted pollutant per unit AL), first by province and sector and then aggregated to the national level. This new CO_2 emission inventory is developed from a framework previously applied to criteria pollutants and tested and improved by comparisons with observations of those species by satellites and ground stations. Reconstructing the framework to estimate China's CO_2 emissions, which has not been done previously, capitalizes on this prior observational validation of energy use and other ALs within it. Four main sectors are included: coal-fired power plants (CPP), industry (IND), transportation (TRA, including on-road and non-road sources), and residential & commercial activities (RES, including fossil fuel use, biofuel use, and open burning of crop residue biomass). Industry is subdivided into cement plants (CEM), iron & steel plants (ISP), other industrial boilers (OIB, including oil power plants as well), and other processes (PRO) (see Supplementary data for details). To avoid double counting, only direct emissions from each sector are estimated. For example, emissions from electricity generation used in steel making are included in CPP but not in ISP. Carbon emitted from combustion of biofuels and biomass was previously in the atmosphere and cycles back to atmospheric CO_2, and thus these two sources are sometimes ignored in long-term assessments. They are important for short-term analysis of atmospheric CO_2, however, and are included in the current inventory of total emissions, although they are omitted when comparing current results to other estimates of CO_2 emissions that exclude them in Section 3.

All of the input parameters of ALs and EFs, with corresponding probability distributions (to be discussed below), are placed in a Monte-Carlo framework. 10,000 trials are performed to estimate the emission uncertainties and to identify the parameters that contribute most to the uncertainties by sector (see Supplementary data for details).

2.1. Activity levels with uncertainties

The ALs include fuel consumption for CPP, TRA, RES, and industrial kilns of CEM and PRO, and industrial output for ISP and non-combustion processes of CEM and PRO. For example, the AL for combustion in CEM kilns is their coal consumption, and the AL for carbonate calcination of CEM is the clinker output.

Data on fossil fuel consumption and industrial production (2005–2009) are obtained from Chinese official energy (NBS, 2010a) and industrial economy statistics (NBS, 2010b), respectively, by sector and province. The ratios of bituminous, lignite, and anthracite coal consumed by each province are estimated based on the production of coal mines by province and inter-provincial transportation flows of coal. To avoid double counting, the fuel consumption by OIB is estimated by subtracting the fuel consumed by CEM, ISP, and PRO from fuel consumed by total industry. Details are described in the Supplementary data.

The uncertainties of ALs vary by sector. For CPP, an independent estimate of coal consumption was previously conducted by the authors, based on the actual operation conditions of individual power plants at the unit level including capacity, annual running hours, and coal consumption per unit generated electricity (expressed as grams of coal equivalent per kilowatt-hours, gce kW^{-1} h^{-1}) (Zhao et al., 2008). The results are close to those reported in energy statistics, suggesting relatively small uncertainty. A normal probability distribution with coefficient of variation (CV) of 5% is accordingly assumed in the current study. For ALs of industrial and residential sectors, we accept the recommendation of the IPCC for countries with less developed statistical systems (IPCC, 2006) and assume normal distributions with CVs of 10% and 20%, respectively.

For transportation, Chinese official energy statistics report only fuel used in commercial activities and are thus incomplete for a national emission inventory. Instead, the oil consumption by on-road vehicles is calculated here as the product of the population of different vehicle types, annual average mileage traveled per vehicle, and average fuel economy of each vehicle type, as reported in (Zhao et al., 2011). A normal distribution with a CV of 16% has been estimated by the authors (Zhao et al., 2011) and is applied in this work. Oil consumption by non-road sources is taken from Zhang et al. (2008). The probability distribution is assumed to be the same as that for on-road vehicles, since there is currently little information available for uncertainty analysis of non-road transportation oil consumption (Zhao et al., 2011).

The biofuel consumption by province is taken from official energy statistics (NBS, 2010a). The amount of crop residues burned in the open field is calculated as the product of crop production, waste-to-grain ratio, and the percentage of residues burned in the field (Zhao et al., 2011). The crop production by province is taken from rural energy statistics (NBS, 2010c). The CVs of biofuel amount and crop production are taken as 30%, in accordance with IPCC (2006). The waste-to-grain ratio and the percentage of residues burned in the field are dependent on crop type and province, respectively, with details described in the Supplementary data.

2.2. Application of provincial-level energy statistics

As stated previously, energy statistics at provincial level are generally used to estimate ALs in this work. Note that China's provincial and national energy statistics are often inconsistent. For 2005–2009, the annual fossil energy consumption levels reported officially for the entire country range 10–14% lower than the sum of provincial energy consumption (NBS, 2010a). On a fuel basis, these differences reach 13–16% and 20–26% for coal and gasoline consumption, respectively. Regarding sectors, the provincial and national statistics match well for CPP, but large differences are found for others. For example, the annual coal consumption reported for IND and RES at the national level for 2005–2009 range 8–25% and 11–30% lower than the sum of provincial-level consumption, respectively. We believe that provincial statistics are more accurate than national statistics, for the following reasons. First, provincial statistics are believed to include more of the sizable output from unregistered small coal mines in China that national statistics have been reported to omit (Sinton, 2001). This bias in the national vs. summed provincial data continues through the most recent statistical datasets (NBS, 2010a), as do other internal inconsistencies suggesting problems in the national totals (Wang and Chandler, 2011). Second, studies of criteria air pollutants have used satellite observations to test emission inventories compiled from provincial energy data, in effect verifying these activity levels instrumentally. One study specifically found the provincial-level statistics to be within the uncertainty bounds of the satellite record of NO_2 over China while the national level statistics were not, and advised against use of the latter in China's emission inventories (Akimoto et al., 2006). Although this conclusion was drawn for 1996–2002, the differences in provincial and national statistics have not diminished over subsequent years (NBS, 2010a), and the conclusion was confirmed to still hold (Zhang et al., 2007). Third, senior officials of China's National Bureau of Statistics (NBS) and National Development and Reform Commission (NDRC) report privately that energy statistics at the national level are routinely adjusted downward, relative to the sums of provincial-level data, in order to reconcile the former with macroeconomic statistics (personal communications with NBS and NDRC officials on condition of anonymity, 2011).

2.3. Emission factors for coal-fired power plants

Field measurements were conducted to estimate the CO_2 EFs for CPP. Detailed measurement methods and results are summarized in the Supplementary data. The mean of CO_2 concentrations in the flue gas for units burning bituminous coal is estimated using Bootstrap simulation to have a normal distribution with a CV of 1.3%. Accordingly, with 10,000 trials of Monte-Carlo simulation, a gamma distribution with central value of 2058 kg CO_2 per metric ton (t) coal is fitted for the EF based on the Kolmogorov–Smirnov test for goodness-of-fit ($p = 0.05$), as shown in Fig. 1 (see Supplementary data for details; note that 1 kg CO_2/t-coal = 48.8 kg CO_2/TJ, based on the average heating value of China's bituminous coal of 20.5 GJ/t-coal (Jin, 2001)). For units burning lignite, only four data points are available and failed to pass the goodness-of-fit test of Bootstrap simulation. A uniform distribution is thus assumed with a range of 1268–1447 kg t^{-1}. Only one test was conducted for anthracite, which cannot be assumed to be representative and the suggested EF by IPCC (2006), expressed as the mass of CO_2 per thermal unit of coal, is therefore adopted. Combined with the ranges of heating values of Chinese domestic anthracite (Jin, 2001), the EF is simulated at 2320 kg t^{-1} with a gamma distribution.

2.4. Emission factors for other sources

For other sources, published EFs obtained by domestic field tests were given preference to complete the EF database for China. In cases where local information is lacking (particularly for PRO and non-road TRA), EFs not specific to China are applied, such as IPCC (2006). For EFs with sufficient domestic measurements, probability distributions are fitted using Crystal Ball, a statistical software package, subject to the Kolmogorov–Smirnov test for goodness-of-fit ($p = 0.05$). For EFs with limited field tests, or those that failed to pass the goodness-of-fit test, probability distributions must be assumed. Table 1 summarizes by sector and fuel the EFs with probability distributions used in this study. Details on their compilation are discussed in Supplementary data. Table 1 includes also the global default EFs of two other databases applied below for comparison, from IPCC (2006) and U.S. Energy Information Administration (USEIA, 2011). Domestic heating values of fuels (Jin, 2001; Yan and Crookes, 2009; Ou et al., 2010; Lai, 2006) are applied to convert the unit of EFs from mass of CO_2 per thermal unit to kg CO_2/t-fuel.

3. Results and Discussions

3.1. Emission trends 2005–2009

China's anthropogenic CO_2 emissions are estimated to have increased from 7126 to 9370 metric million tons (Mt CO_2) from

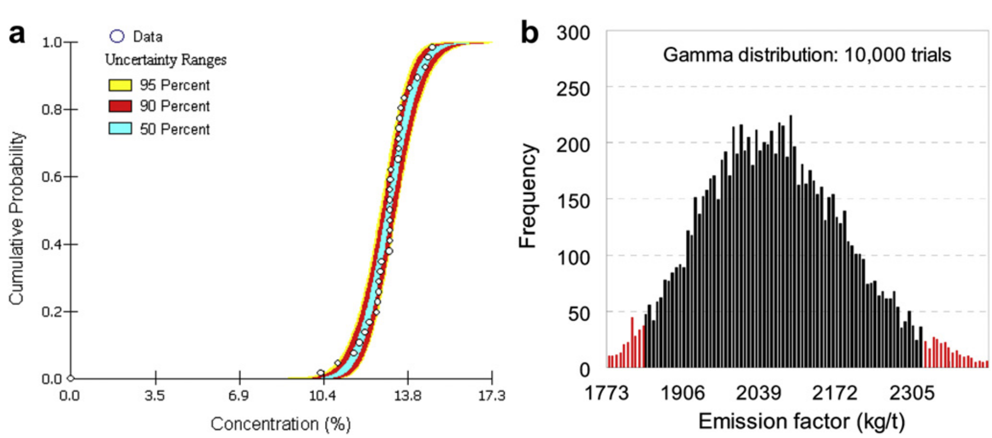

Fig. 1. Uncertainty analysis of the emission factor for power plants burning bituminous coal: (a) probability bands of flue gas concentrations; (b) distribution of the emission factor determined by Monte Carlo simulation. The red bars are beyond the 95% confidence intervals (CIs). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
China's CO_2 emission factors (EF) with probability distributions for (a) Coal-fired power plants (CPP), (b) Transportation (TRA), (c) Industry (IND), and (d) Residential & commercial activities (RES). Upper and lower bounds are given for uniform distributions, and 95% CIs are given for other distributions. The default emission factors by IPCC and USEIA are also listed for comparison. Unless noted, the unit is kg CO_2/t-fuel for CPP, TRA, RES and other industrial boilers (OIB), and kg CO_2/t-product for iron & steel plants (ISP) and industrial processes (PRO).

Sub-sector/fuel	This study			IPCC	USEIA
	EF (range)	Distribution	Original data source	EF	EF
(a) Coal-fired power plants (CPP)					
Bituminous	2058 (1840–2342)	Gamma	Tests by authors	1937	1813
Lignite	1268–1447	Uniform	Tests by authors	1236	1130
Anthracite	2320 (2176–2467)	Gamma	IPCC (2006); USEIA (2011); Jin (2001)	2320	2319
(b) Transportation (TRA)					
On-road: gasoline	3069 (2516–3621)	Lognormal	Yan and Crookes (2009); Ou et al. (2010); Wang and Fu (2010)	3194	2942
On-road: diesel	3181 (2608–3753)	Lognormal	Yan and Crookes (2009); Ou et al. (2010); Wang and Fu (2010)	3194	2942
Non-road: coal	1970 (1409–2234)	Lognormal	IPCC (2006); Yan and Crookes (2009); Ou et al. (2010)	1970	–
Non-road: diesel	3194 (2618–3766)	Lognormal	IPCC (2006); Yan and Crookes (2009); Ou et al. (2010)	3194	2942
Non-road: small engines	2987 (2449–3525)	Lognormal	IPCC (2006); Yan and Crookes (2009); Ou et al. (2010)	2987	2942
(c) Industry (IND)					
Cement plants (CEM)					
Process (kg CO_2/t-clinker)	549 (522–578)	Weibull	Lei et al. (2011); Cui and Liu (2008)	520	–
Kiln (kg CO_2/t-coal)	1731 (1094–2368)	Normal	Wang et al. (2009a); Zhang et al. (2001); Wu and Chen (2001)	1937	1813
Iron & steel plants (ISP)					
Total (kg CO_2/t-steel)	2067 (1510–2624)[a]	Normal	Shangguan et al. (2010); Jiang et al. (2009); CISA (2010)		
Sinter production				200	–
Coke oven				560	–
Open hearth furnace				1720	–
Basic oxygen furnace				1460	–
Electric arc furnace				80	–
Other boilers (OIB)					
Bituminous	1923 (1215–2631)	Normal	Wang et al. (2009a); Zhang et al. (2001)	1937	1813
Lignite	1111–1408	Uniform	IPCC (2006); USEIA (2011); Jin (2001)	1236	1130
Anthracite	2320 (2176–2467)	Gamma	IPCC (2006); USEIA (2011); Jin (2001)	2320	2319
Residual fuel oil	3248 (3014–3483)	Weibull	IPCC (2006); USEIA (2011); USEPA (2002); Zhang et al. (2009); Yan and Crookes (2009); Ou et al. (2010)	3336	3219
Other oil	3086 (2870–3295)	Weibull	IPCC (2006); USEIA (2011); USEPA (2002); Zhang et al. (2009); Yan and Crookes (2009); Ou et al. (2010)	3194	2988
Natural gas	3116 (2785–3448)	Normal	IPCC (2006); USEIA (2011); USEPA (2002); Zhang et al. (2009); Lai (2006)	3254	2962
Processes (PRO)					
Lime production process	750 (691–809)	Normal	IPCC (2006)	750	–
Industrial kiln (kg CO_2/t-coal)	1731 (1094–2368)	Normal	Wang et al. (2009a); Zhang et al. (2001); Wu and Chen (2001)	1937	1813
NH_3 production: coal	4582 (2328–6798)	Normal	Zhou et al. (2010)	4582	–
NH_3 production: oil	3273 (1666–4880)	Normal	Zhou et al. (2010)	3273	–
NH_3 production: gas	2104 (1065–3143)	Normal	Zhou et al. (2010)	2104	–
Pb production	520 (265–775)	Normal	IPCC (2006)	520	–
Zn production	1720 (877–2563)	Normal	IPCC (2006)	1720	–
Al production	1600 (816–2384)	Normal	IPCC (2006)	1600	–
Glass production	200 (102–298)	Normal	IPCC (2006)	200	–
(d) Residential & commercial activities (RES)					
Coal boiler	1923 (1215–2631)	Normal	Wang et al. (2009b); Zhang et al. (2001)	1937	1850
Coal stove	2170 (1276–2670)	Weibull	Zhang and Smith (2000)	1937	1850
Oil combustion	3086 (2870–3295)	Weibull	IPCC (2006); USEIA (2011); USEPA (2002); Zhang et al. (2009); Yan and Crookes (2009); Ou et al. (2010); Zhang and Smith (2000)	3194	2988
Natural gas combustion	3144 (2791–3493)	Weibull	IPCC (2006); USEIA (2011); USEPA (2002); Zhang et al. (2009); Lai (2006); Zhang and Smith (2000)	3254	2962
Biofuel: straw waste	1284 (594–1658)	Beta	Zhang and Smith (2000); Li (2007); Li et al. (2007)	N/A	–
Biofuel: wood	1496 (1234–1675)	Weibull	Zhang and Smith (2000); Li (2007); Li et al. (2007)	N/A	–
Biomass open burning	1262–1558	Uniform	Li et al. (2007)	N/A	–

[a] The value for 2005. The values for 2006, 2007, 2008 and 2009 were estimated at 1896, 1870, 1855, 1811 kg CO_2/t-steel, respectively, reflecting changes in the technology distribution needed for this output-based AL.

2005 to 2009, reflecting an annual growth rate of 7.1% (Fig. 2(a), labeled as EF-Author). Among all sectors, IND contributed 41% of the total national emissions in 2005, followed by CPP (32%), RES (20%, two-thirds of which was from biofuel use and open biomass burning), and TRA (7%), as shown in Fig. 2(b). From 2005 to 2009, emissions from IND increased fastest, particularly from ISP, with an annual growth rate of 13%. This swift growth increased the IND share of national emissions to 46% in 2009. With rapid urbanization and motorization, emissions from TRA increased by 42% from 2005 to 2009, and its share of the national total increased slightly to 8% in 2009. Due to reduced use of solid fuels, a 3% reduction of emissions from RES was achieved during the same period. Regarding CPP, a 29% growth of emissions is estimated but its share of the national total decreased slightly to 31%.

For comparison, CO_2 emissions are also estimated using the same ALs but applying default EFs from IPCC and USEIA (labeled EF-IPCC and EF-USEIA, respectively, in Fig. 2). For biofuel use and open biomass burning, default EFs are unavailable and the EF-IPCC and EF-USEIA estimates use those compiled in this work. For other sectors lacking USEIA EFs, the EF-USEIA estimates employ IPCC EFs. The differences are relatively small for annual total emissions, particularly between the results of EF-Author and EF-IPCC. The

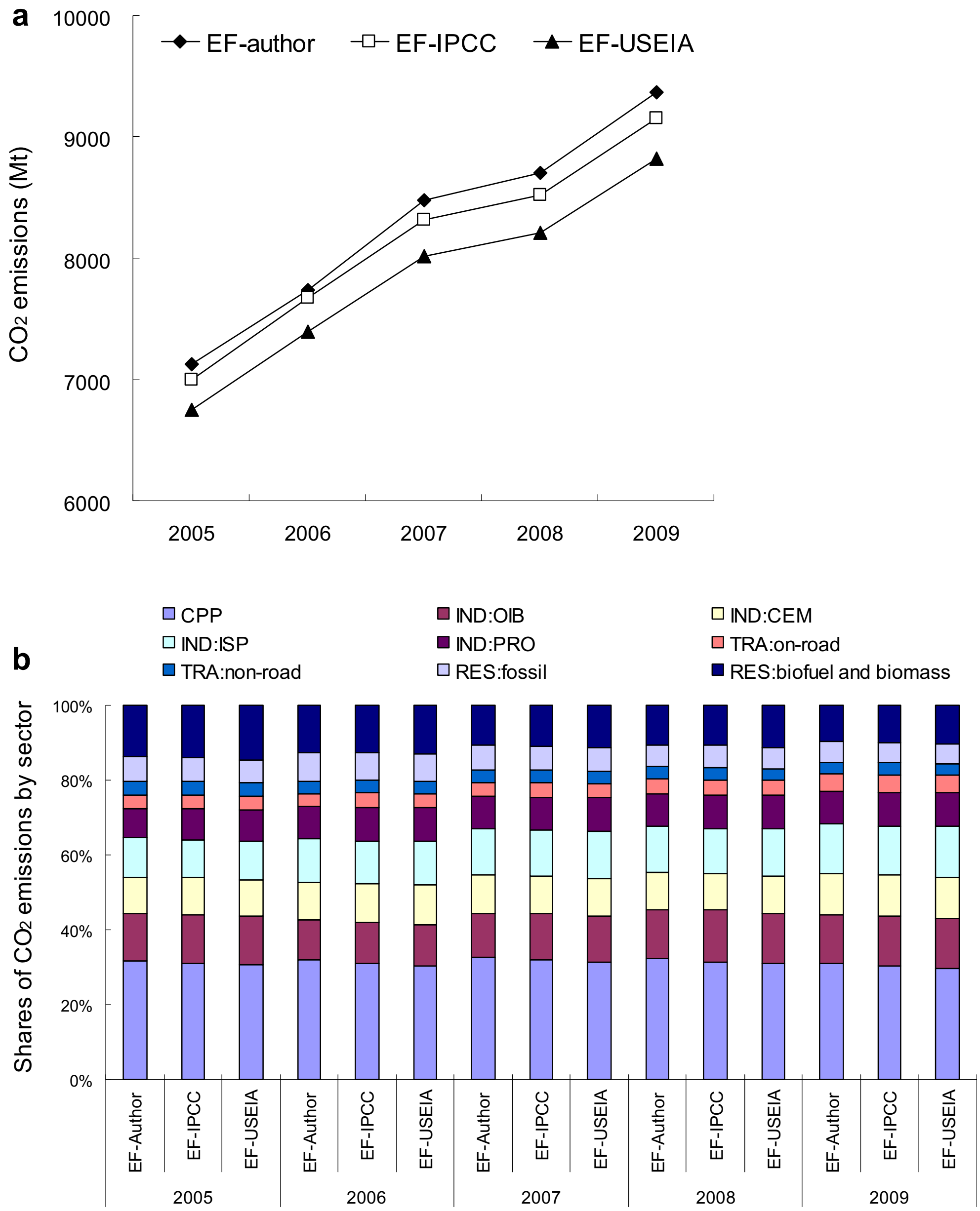

Fig. 2. The total annual emissions (a) and shares by sector (b) of Chinese anthropogenic CO_2 from 2005 to 2009, using common activity levels but different sets of emission factors (EFs). EF-Author, EF-IPCC, and EF-USEIA represent the emissions estimated based on the EF database developed in this study, by IPCC, and USEIA, respectively.

estimated annual emissions of EF-Author over 2005–2009 range 0.8–2.3% and 4.4–5.9% higher, respectively, than those of EF-IPCC and EF-USEIA (Fig. 2(a)). However, larger discrepancies are found for emissions in particular sectors. The 2005 emission from ISP using the domestic EF is estimated as 9% higher than that using IPCC EFs. This is likely due to poorer average energy efficiency of China's ISP compared to that assumed in IPCC default EFs, explained by China's low penetration of electric-arc furnaces using waste steel inputs, and high reliance on more energy-intensive inputs including pig iron (Wang et al., 2007). Using EFs obtained through field measurements by the authors and Zhang and Smith (2000), respectively, emissions for power plants and residential fossil fuel combustion are estimated to range 4.2–4.8% and 3.1–5.4% higher than those with IPCC EFs, and 8.6–9.6% and 8.3–10.1% higher than those with USEIA ones. The differences can be attributed to many factors such as the fuel quality and the operating conditions when the tests were made. The results from application of domestic EFs obtained by field measurements can be quite uncertain, especially due to limited sampling sites, motivating the uncertainty analysis presented below. Due to combustion inefficiency of some industrial boilers and kilns, the EF-Author emissions from those sources are somewhat lower than those of EF-IPCC. However, these are insufficient to compensate for the higher emissions from other sectors noted above.

3.2. *Quantification of uncertainties*

The uncertainties of China's CO_2 emissions in 2005 are shown by sector in Table 2, expressed as the 95% CIs around the central estimates. The uncertainty of national total anthropogenic emissions is estimated at −9% to +11% (expressed as a 95% confidence interval, CI), smaller than the uncertainty range of 15–20% reported

Table 2
Total Chinese CO_2 emissions and uncertainties in 2005 by source categories, and the parameters contributing most to the uncertainties. The estimated emissions are expressed as Mt CO_2, followed by the 95% CIs around the central estimates. Ranking parameters are judged by their percentage contributions to the variance of corresponding emissions.

Sector	CO_2 emissions (95% CI)	Parameter (percentage contribution to the variance)	
		1st	2nd
Coal-fired power plants	2259 (−12% to +14%)	Coal consumption (44%)	EF (bituminous) (33%)
Industry	2906 (−15% to +18%)		
Cement plants	674 (−24% to +26%)	Cement production (52%)	EF (kiln) (27%)
Iron & steel plants	767 (−31% to +39%)	EF (51%)	Steel production (27%)
Other boilers	908 (−17% to +19%)	EF (bituminous) (41%)	Coal consumption (25%)
Processes	557 (−23% to +24%)	EF (kiln) (42%)	EF (NH_3 production with coal) (18%)
Transportation	508 (−14% to +15%)		
On-road vehicles	258 (−18% to +19%)	Diesel consumed by HDDV[a] (28%)	Gasoline consumed by LDGV[b] (24%)
Non-road sources	250 (−19% to +20%)	Oil consumed by ship (27%)	Oil consumed by rural machine (24%)
Residential & commercial	1453 (−28% to +32%)		
Fossil fuel	470 (−35% to +38%)	Coal consumption (53%)	EF (stove) (17%)
Biofuel and biomass	983 (−37% to +46%)	Amount of straw as biofuel (41%)	EF of straw burning as biofuel (19%)
Coal combustion	4538 (−11% to +13%)		
Fossil fuel use	5516 (−10% to +11%)		
Fossil fuel use and cement	5938 (−9% to +10%)		
Total	7126 (−9% to +11%)		

[a] Heavy duty diesel vehicles.
[b] Light duty gasoline vehicles.

by Gregg et al. (2008). The difference can be attributed to the more detailed source categories in the current study, which significantly reduce the random errors by the "compensation-of-error" mechanism realized through Monte-Carlo simulation (Zhao et al., 2011). The uncertainty estimated by Gregg et al. (2008) is an approximation, based mainly on the magnitude of subsequent revisions of national energy statistics, and thus differs from that of this work. In order to compare emission estimates with those of varied scopes reported in other studies (CDIAC, 2010; PBL, 2010; USEIA, 2010), the uncertainties of emissions from coal combustion, fossil fuel combustion, and fossil fuel combustion plus cement processes are also estimated, at −11% to +13%, −10% to +11%, and −9% to +10%, respectively. Regarding sectors, the uncertainty of emissions from CPP is the smallest (−12% to +14%), attributed to relatively high accuracy of China's power plant data at the unit level (Zhao et al., 2008). The uncertainty of RES is the largest, due to poor statistics on rural energy consumption and limited field tests on EFs, particularly for biofuel use and open biomass burning.

Shown in Table 2 as well are the parameters contributing most to the emission uncertainty by sector. For industrial sub-sectors, EFs are the strongest determinants of the emission uncertainties except for CEM. China's industry is a mixture of technologies ranging widely in energy efficiency, and considerable variation exists between EF estimates based on the limited domestic tests that are currently available. More field measurements are therefore recommended to narrow the CIs of domestic CO_2 EFs and to reduce the emission uncertainties for industrial sub-sectors.

For other sectors, however, ALs (i.e., fuel consumption in most cases), as opposed to EFs, are estimated to contribute more to the variance of CO_2 emissions. The uncertainties of oil consumption for TRA and coal consumption for RES are each responsible for over 50% of the variances of CO_2 emissions for the corresponding sub-sectors, and of coal consumption for 44% of the variance in CPP, as shown in Table 2. In the case of RES specifically, there is currently no independent source to check the accuracy of fuel consumption, with uncertainties now dependent on IPCC (2006). Improvement in energy use statistics, particularly for rural residential fuel consumption, is the most important step towards more precise quantification of CO_2 emissions from RES in China. More generally, improving the accuracy of ALs, again chiefly through better energy statistics, is one of the biggest research priorities to reduce the uncertainties of China's CO_2 emissions overall.

3.3. Provincial and gridded emissions

Provided in Table 3 are the detailed data of provincial CO_2 emissions for 2005 and 2009. Besides total emissions of anthropogenic origin, the emissions omitting biofuel use and biomass open burning are also given (the numbers in the parentheses in Table 3), following the convention. As shown in Fig. 3(a), the distribution of emissions is influenced mainly by the size of the economies of the provinces and their population densities. The largest emissions are found in coastal provinces in east and north-central areas including Shandong, Jiangsu, and Hebei. In 2005, east, north-central, and south-central China (as identified in Table 3), covering only 35% of the country's territory but containing 69% of the national population and responsible for 78% of China's GDP, are estimated to account for 73% of the national emissions of anthropogenic CO_2. During 2005–2009, however, the emission growth rates of the coastal provinces are estimated to have been lower than those of interior provinces, although the absolute emissions of the interior provinces were generally small in comparison. Regarding sector distribution by region, the RES shares of total emissions were larger for interior provinces than coastal provinces, although these shares were declining swiftly. For example, 37% of emissions were from RES in southwest China in 2005 and only 14% for the east, but by 2009, the respective values had deceased to 23% and 11%. The main reasons for this regional disparity include: 1) more solid fuels are used in less developed rural areas in the west; and 2) industry and vehicles are more concentrated in the urbanized east.

To be applicable for atmospheric carbon simulation, annual emissions at provincial level are allocated into a $0.25° \times 0.25°$ grid system, applying the methods described in Zhao et al. (2012). Shown in Fig. 3(b) and (c) are the gridded emissions of China's anthropogenic CO_2 in 2005 and 2009, respectively.

3.4. Comparison to prior estimates

As shown in Fig. 4, the estimated CO_2 emissions with 95% CIs are compared with other estimates by the PBL Netherlands Environmental Assessment Agency (PBL, 2010), USEIA (2010), and CDIAC (2010) for: a) coal use; b) fossil fuel use; and c) fossil fuel use plus cement production. To be consistent with the emission categories of those studies, emissions from non-combustion processes (except carbonate calcination in cement production), biofuel combustion,

Table 3
China's anthropogenic CO_2 emissions in 2005 and 2009 by province and sector (Mt CO_2). CPP, IND, TRA, and RES indicate the coal-fired power plants, industry, transportation, and residential & commercial activities, respectively.

Province	2005					2009				
	CPP	IND	TRA	RES	Total[a]	CPP	IND	TRA	RES	Total[a]
North-central										
Beijing	22	53	15	23	112 (110)	14	39	21	24	98 (97)
Tianjin	36	58	27	7	129 (127)	38	96	25	10	168 (162)
Hebei	135	295	39	87	556 (509)	163	424	49	76	712 (666)
Shanxi	141	102	15	43	301 (286)	183	145	19	53	399 (378)
Inner Mongol	107	75	14	53	249 (226)	228	112	24	66	431 (410)
Northeast										
Liaoning	93	169	20	50	332 (301)	118	193	32	46	389 (356)
Jilin	39	74	11	46	170 (144)	59	89	16	37	201 (175)
Heilongjiang	76	62	14	53	204 (160)	76	90	20	61	246 (201)
East										
Shanghai	77	74	28	7	185 (185)	59	67	34	13	172 (172)
Jiangsu	220	219	28	75	542 (473)	232	319	47	58	656 (604)
Zhejiang	106	145	25	20	296 (281)	157	171	40	27	394 (381)
Anhui	76	83	18	82	259 (197)	121	161	29	80	391 (319)
Fujian	63	74	10	21	168 (157)	81	120	18	24	244 (230)
Jiangxi	39	75	8	34	156 (132)	47	114	13	23	197 (178)
Shandong	230	306	48	83	667 (610)	279	411	71	99	859 (800)
South-central										
Henan	178	154	33	86	451 (394)	203	306	44	80	632 (572)
Hubei	65	112	16	59	252 (208)	63	195	24	75	357 (316)
Hunan	50	117	14	82	263 (212)	61	169	20	69	319 (275)
Guangdong	141	170	40	51	403 (357)	176	255	50	62	543 (502)
Guangxi	26	66	10	87	190 (105)	37	113	15	77	243 (170)
Hainan	4	11	3	6	25 (19)	8	16	4	7	35 (30)
Southwest										
Chongqing	21	53	6	43	122 (90)	33	95	10	30	169 (150)
Sichuan	70	87	16	118	291 (193)	63	196	26	101	386 (308)
Guizhou	60	54	5	82	201 (155)	107	73	8	62	250 (218)
Yunnan	29	63	12	44	148 (119)	67	95	17	38	217 (190)
Tibet	0	1	1	0	2 (2)	0	1	2	1	4 (3)
Northwest										
Shaanxi	60	39	10	38	146 (126)	81	95	16	45	238 (209)
Gansu	35	40	7	26	107 (92)	42	48	10	26	127 (110)
Qinghai	5	9	2	8	25 (22)	10	17	3	7	37 (34)
Ningxia	24	16	3	8	51 (46)	49	30	4	6	89 (86)
Xinjiang	32	51	8	31	122 (105)	49	77	12	30	168 (150)
Total	2259	2906	508	1453	7126 (6142)	2905	4331	721	1414	9370 (8452)

[a] The numbers in the parentheses indicate the results omitting biofuel and biomass burning.

and biomass open burning otherwise included in the current study are excluded in the comparisons. Note that PBL and USEIA have revised their estimates for some years based on newer information. For example, in the most recent updates of China's estimated CO_2 emissions from fossil fuel combustion in 2008, USEIA increased a previous estimate of 6534–6804 Mt CO_2, while PBL decreased its estimate from 7005 to 6826. Such revisions are likely due to adjustments in China's energy consumption reported by different sources upon which they rely; Fig. 4 reports their latest estimates. PBL estimated China's annual emissions to range 3.9–7.2% higher than CDIAC for fossil fuel use plus cement production during 2005–2009, with the largest difference 543 Mt CO_2 in 2009. The emissions from fossil fuel use estimated by PBL were as much as 490 Mt CO_2 higher than those of USEIA (in 2000, not shown in Fig. 4), but 291 Mt CO_2 lower for 2009.

For 2005–2008, the annual emissions estimated by other studies are lower than those in this work, but most values are within the 95% CIs provided by this study. The largest differences with this study are found for CDIAC, which estimated the annual emissions to range 10–15%, 8–13%, and 5–10% lower than those by this work for coal combustion, fossil fuel combustion, and fossil fuel combustion plus cement production, respectively, over 2005–2009. For 2007, particularly, CDIAC estimates are below the lower bounds of the 95% CIs of this study. Use of provincial-level energy statistics in the current work is likely the primary determinant of this difference. Besides these energy data, the higher emissions of this study are attributed partly to the use of higher emission factors for certain carbon-intensive sectors such as CPP and ISP. Compared to 2007, the differences in emission estimates between this work and other studies decline in 2008, and the emissions estimated by USEIA and PBL for 2009 exceed those of this study. A reason might be the rising effectiveness of the national policy on improving energy efficiencies, which is captured by the methods of the current study as described below.

3.5. Effects of national policies since 2006

China has been implementing a national policy of energy conservation and emission reduction since 2006. Small and old plants have gradually been replaced with larger, more energy efficient ones equipped with advanced emission control devices, particularly in sectors with high energy intensities and large emissions of criteria pollutants and CO_2. These include coal-fired power generation, cement production, and iron & steel production (Zhao et al., 2008; Lei et al., 2011). Shown in Fig. 5 are the trends of outputs and CO_2 emissions of the three sectors. Coal-fired electricity generation, cement production, and steel production increased by 46%, 54%, and 87%, respectively, from 2005 to 2009. The increase in coal-fired power generation slowed after 2007, attributed to declining construction of new coal-fired power units in response to increased capacity of other types of power generation. The increase of cement and steel production from 2007 to

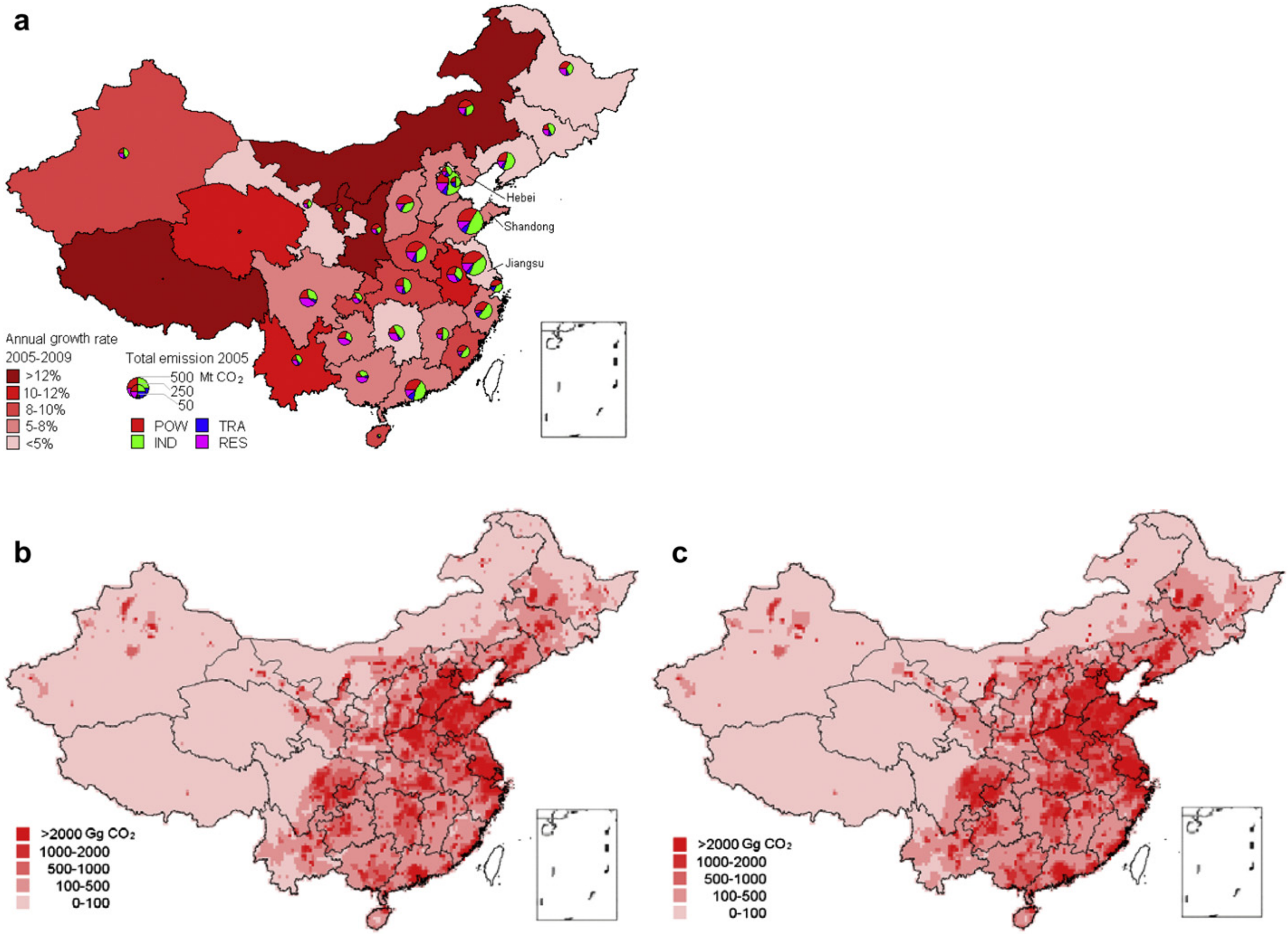

Fig. 3. Spatial distribution of China's CO_2 emissions. (a) The provincial emissions in 2005 and the relative changes between 2005 and 2009 (the sizes of the pie graphs indicate absolute emissions by sector in 2005), and the gridded emissions in 2005 (b) and 2009 (c) at the resolution of 0.25° × 0.25°.

2008 is modest, attributed to production limitations imposed for the Beijing Olympics and the economic downturn at the end of 2008. To stimulate the economy, the government subsequently made huge investments in infrastructure construction, resulting in

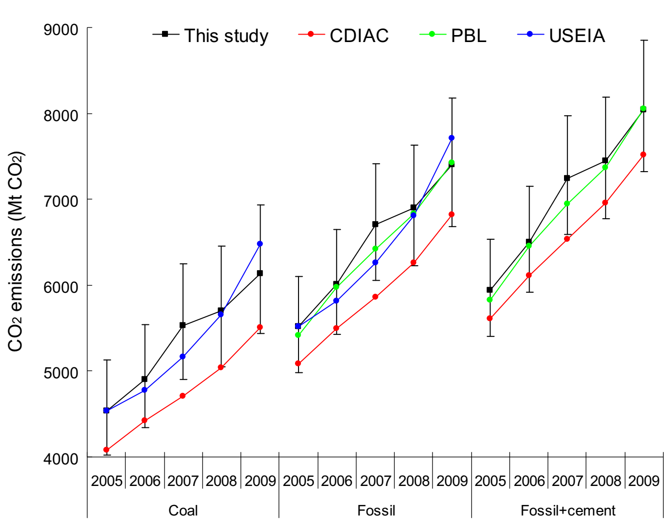

Fig. 4. The comparison of annual CO_2 emissions in China between this study and other results. The black vertical lines represent the 95% CIs of this study.

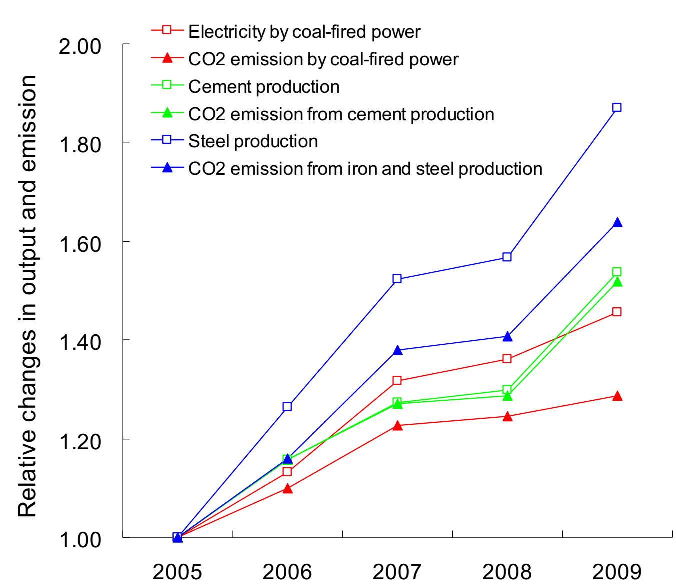

Fig. 5. The output and CO_2 emissions of coal-fired power sector, cement production, and iron & steel production in China for 2005–2009. All the values are normalized to the levels in 2005.

a sharp increase in cement and steel production in 2009. CO_2 emissions from CPP and ISP are estimated to have increased by 29% and 64%, respectively, over the five years, much slower than the respective increases in electricity and cement output. This reflects the benefits to carbon emissions of the national policy of energy conservation and emission reduction. Through 2005–2009, over 50 GW of small and energy-inefficient electricity-generating units were shut down, and all newly built units were large (300 MW or above) and comparatively energy efficient. As captured by this study's unit level analyses, the share of capacities of power units of at least 600 MW increased from 15% in 2005 to 38% in 2009, while the share of units less than 100 MW decreased from 18% to 4% (Zhao et al., 2008). The penetration of large units reduced the coal consumption per unit electricity from 370 gce kW^{-1} h^{-1} in 2005 to 340 in 2009. This is the main reason that CO_2 emissions from CPP grew more slowly than electricity generation. Moreover, the share of coal with relatively high heating values (i.e., anthracite) has been shrinking in recent years (see Table S1 in the Supplementary data) and this also slowed the increase of CO_2 emissions. Similarly, through the retirement of small plants and the greater use of waste heat, the national level of energy consumption per unit production of steel decreased from 694 kgce/t-steel in 2005 to 614 in 2009 (CISA, 2011), thereby significantly slowing the increase in CO_2 emissions from ISP. Meanwhile, the penetration of electric arc furnace, which has lower CO_2 emission factor than basic oxygen furnace, is still limited in China's iron and steel production (less than 15% according to CISA (2010)). This implies that there is further potential for CO_2 abatement of iron & steel production by expanding the share of electric arc furnace in the sector. For CEM, however, the national policy appears to have had less impact on CO_2 emissions. From 2005 to 2009, the fraction of precalciner kilns, the most energy-efficient technology, increased from 44% to 70% (Lei et al., 2011), and CO_2 emissions from combustion increased by 48%, slower than the production increase of 54%. Nevertheless, there is currently no economically viable technology to mitigate CO_2 emissions from carbonate calcination, which contributed 63% of total emissions from CEM in 2005, although ground industrial slag can be blended with clinker to reduce somewhat the total clinker demand of the cement-making process. In the near future, the only major way to control CO_2 emissions from CEM may be through reducing the growth of production itself. Overall, the national policy of energy conservation and emission reduction constrained the growth of CO_2 emissions compared to that of product outputs for heavy industrial sectors; its extension to other sources like residential boilers could further reduce national emissions.

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Appendix A. Supplementary data

Supplementary data related to this article can be found online at doi:10.1016/j.atmosenv.2012.05.027.

References

Akimoto, H., Ohara, T., Kurokawa, J., Horii, N., 2006. Verification of energy consumption in China during 1996–2003 by using satellite observational data. Atmospheric Environment 40, 7664–7667.

Carbon Dioxide Information Analysis Center (CDIAC), 2010. People's Republic of China Fossil-fuel CO2 Emissions. Available at: http://cdiac.ornl.gov/ftp/trends/emissions/prc.dat.

China Iron and Steel Association (CISA), 2010. China Steel Yearbook 2006–2010. The Editorial Board of China Steel Yearbook, Beijing (in Chinese).

China Iron and Steel Association (CISA), 2011. The Review of Energy Conservation and Emission Reduction During the 11th Five-Year-Plan Period. Available at: http://www.chinaisa.org.cn/news.php?id=2170947 (in Chinese).

Cui, S.P., Liu, W., 2008. Analysis of CO_2 emission mitigation potential in cement producing processes. China Cement 4, 57–59 (in Chinese).

Gregg, J.S., Andres, R.J., Marland, G., 2008. China: emissions pattern of the world leader in CO_2 emissions from fossil fuel consumption and cement production. Geophysical Research Letter 35, L08806. doi:10.1029/2007GL032887.

Intergovernmental Panel on Climate Change (IPCC), 2006. IPCC Guidelines for National Greenhouse Gas Inventories. IPCC National Greenhouse Gas Inventories Programme.

Jiang, Q., Liu, T.T., Xing, F.F., Han, S., Wang, Y.M., 2009. CO_2 emission inventory and emission-reducing potential analysis in representative iron & steel enterprises. Metallurgical Information Review 3, 15–18 (in Chinese).

Jin, W.Q., 2001. Power Plant Boiler. China Waterpower Press, Beijing (in Chinese).

Lai, Y.K., 2006. The Choice of standards on natural gas calorific value. Energy Policy Research 1, 32–37 (in Chinese).

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

Li, X.H., 2007. Characterization of Air Pollutants Emitted from Biomass Burning in China. Ph.D thesis, Tsinghua University, Beijing (in Chinese).

Li, X.H., Wang, S.X., Duan, L., Hao, J.M., Li, C., Chen, Y.S., et al., 2007. Particulate and trace gas emissions from open burning of wheat straw and corn stove in China. Environmental Science & Technology 41, 6052–6058.

National Bureau of Statistics (NBS), 2010a. China Energy Statistical Yearbook 2006–2010. China Statistics Press, Beijing (in Chinese).

National Bureau of Statistics (NBS), 2010b. China Industry Economy Statistical Yearbook 2006–2010. China Statistics Press, Beijing (in Chinese).

National Bureau of Statistics (NBS), 2010c. China Rural Statistical Yearbook 2006–2010. China Statistics Press, Beijing (in Chinese).

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

PBL Netherlands Environmental Assessment Agency (PBL), 2010. No Growth in Total Global CO2 Emissions in 2009. Available at: http://www.pbl.nl/en/publications/2010/No-growth-in-total-global-CO2-emissions-in-2009.

Shangguan, F.,Q., Zhang, C.X., Hu, C.Q., Li, X.P., Zhou, J.C., 2010. Estimation of CO_2 emission in Chinese steel industry. China Metallurgy 20, 37–42 (in Chinese).

Sinton, J.E., 2001. Accuracy and reliability of China's energy statistics. China Energy Review 12, 373–383.

Streets, D.G., Jiang, K.J., Hu, X.L., Sinton, J.E., Zhang, X.Q., Xu, D.Y., et al., 2001. Recent reductions in China's greenhouse gas emissions. Science 294, 1835–1837.

Su, W., 2009. Letter Including Autonomous Domestic Mitigation Actions. Appendix II-Nationally Appropriate Mitigation Actions of Developing Country Parties, United National Framework Convention on Climate Change. Available at: http://unfccc.int/files/meetings/cop_15/copenhagen_accord/application/pdf/chinacphaccord_app2.pdf.

U.S. Energy Information Administration (USEIA), 2010. International Energy Statistics. Available at: http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=90&pid=44&aid=8.

U.S. Energy Information Administration (USEIA), 2011. Voluntary Reporting of Greenhouse Gases Program Fuel Carbon Dioxide Emission Coefficients. Available at: http://www.eia.doe.gov/oiaf/1605/coefficients.html.

U.S. Environmental Protection Agency (USEPA), 2002. Compilation of Air Pollutant Emission Factors (AP-42). Available at: http://www.epa.gov/ttn/chief/ap42/index.html.

Wang, H.K., Fu, L.X., 2010. Developing a high-resolution vehicular emission inventory by integrating an emission model and a traffic model: part 1-modeling fuel consumption and emissions based on speed and vehicle-specific power. Journal of the Air and Waste Management Association 60, 1463–1470.

Wang, K., Wang, C., Lu, X.D., Chen, J.N., 2007. Scenario analysis on CO_2 emissions reduction potential in China's iron and steel industry. Energy Policy 35, 2320–2335.

Wang, S.X., Zhao, X.J., Li, X.H., Wei, W., Hao, J.M., 2009a. Emission characteristics of fine particles from grate firing boilers. Environmental Science 30, 963–968 (in Chinese).

Wang, S.X., Wei, W., Du, L., Li, G.H., Hao, J.M., 2009b. Characteristics of gaseous pollutants from biofuel-stoves in rural China. Atmospheric Environment 43, 4148–4154.

Wang, Y.J., Chandler, W., 2011. Understanding Energy Intensity Data in China. Carnegie Endowment for International Peace. Available at: http://carnegieendowment.org/files/chinese_energy_intensity.pdf.

Wu, Z.X., Chen, W.Y., 2001. The Diversified Clean Energy Resources Strategies with Coal as the Backbone. Tsinghua University Press, Beijing (in Chinese).

Yan, X.Y., Crookes, R.J., 2009. Reduction potentials of energy demand and GHG emissions in China's road transport sector. Energy Policy 37, 658–668.

Zhang, C.Y., Wang, S.X., Xing, J., Zhao, Y., Hao, J.M., 2008. Current status and future projections of NO_x emissions from energy related industries in China. Acta Scientiae Circumstantiae 28, 2470–2479 (in Chinese).

Zhang, J.F., Ge, S., Bai, Z.P., 2001. Boiler briquette coal versus raw coal: part II-energy, greenhouse gas, and air quality implications. Journal of the Air and Waste Management Association 51, 534–541.
Zhang, J.F., Smith, K.R., 2000. Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors. Atmospheric Environment 34, 4537–4549.
Zhang, M., Mu, H.L., Ning, Y.D., 2009. Accounting for energy-related CO_2 emission in China, 1991–2006. Energy Policy 37, 767–773.
Zhang, Q., Streets, D.G., He, K.B., Wang, Y.X., Richter, A., Burrows, J.P., et al., 2007. NO_x emission trends for China, 1995–2004: the view from the ground and the view from space. Journal of Geophysical Research 112, D22306. doi:10.1029/2007JD008684.
Zhao, Y., Nielsen, C.P., McElroy, M.B., Zhang, L., Zhang, J., 2012. CO emissions in China: uncertainties and implications of improved energy efficiency and emission control. Atmospheric Environment 49, 103–113.
Zhao, Y., Nielsen, C.P., Lei, Y., McElroy, M.B., Hao, J.M., 2011. Quantifying the uncertainties of a bottom-up emission inventory of anthropogenic atmospheric pollutants in China. Atmospheric Chemistry & Physics 11, 2295–2308. doi:10.5194/acp-11-2295-2011.
Zhao, Y., Wang, S.X., Duan, L., Lei, Y., Cao, P.F., Hao, J.M., 2008. Primary air pollutant emissions of coal-fired power plants in China: current status and future prediction. Atmospheric Environment 42, 8442–8452.
Zhou, W.J., Zhu, B., Li, Q., Ma, T.J., Hu, S.Y., Griffy-Brown, C., 2010. CO_2 emissions and mitigation potential in China's ammonia industry. Energy Policy 38, 3701–3709.