China's international trade and air pollution in the U.S.

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Materials and Methods

Methods Summary

Calculation of emissions embodied in exports and imports is based on an input-output analysis of the monetary outputs of the economic processes required to produce a particular good or service, multiplied by sector-specific emission intensities. Emissions from ocean shipping vessels are not included in the analysis. Sectoral emission intensities are calculated as total Chinese emissions (which are estimated by a technology-based, bottom-up approach) divided by total monetary outputs from the respective sectors. We use a Monte Carlo method to quantify uncertainty associated with errors in emission factors, economic statistics and the input-output analysis itself. Emissions of carbon dioxide (CO_2) are calculated with a similar approach, and the resulting emissions embodied in trade are consistent with previous studies. The global chemical transport model GEOS-Chem (version 8-03-02; on the 2.5 °long x 2 °lat grid) is used to simulate the impacts of trade-related pollution on global atmospheric environment.

1. Input-Output Model

Our study is based on an input-output analysis (IOA) that captures indirect environmental impacts caused by upstream production and is thus suitable for estimating embodied emissions (1-3). The method is used commonly for analyzing trade-induced emissions of carbon dioxide (CO_2) (4-8).

Figure S1 shows the general methodology for this study. For a given economic sector, emissions embodied in exports/imports are calculated as trade-related monetary outputs multiplied by emission intensity deduced as total emissions of China divided by total monetary outputs. Total emissions are estimated with a technology-based bottom-up approach (9, 10) and total outputs and trade-related outputs are derived based on the IOA. To remove to impact of inflation on the monetary outputs, the producer price index (PPI) (11) is used to adjust all monetary data based on prices in 2005 for a consistent analysis over 2000-2009.

1.1 A general structure for calculating emissions embodied in international trade

Emissions embodied in exports (EEE) result from production and transportation of goods for exports. As shown in Eq. 1, they are calculated as the sum over all related sectors of exports ($\boldsymbol{X}^e$; in monetary units) multiplied by emission intensity ($\boldsymbol{F}$). Correspondingly, total emissions in China (P; including EEE and those related to domestic consumption) are calculated as the sum over all sectors of emission intensity multiplied by total monetary outputs ($\boldsymbol{X}$):

$$\text{EEE} = \boldsymbol{F} \cdot \boldsymbol{X}^e \qquad (1)$$

$$\text{P} = \boldsymbol{F} \cdot \boldsymbol{X} \qquad (2)$$

Here $\boldsymbol{X}$ represents total outputs to meet both final demand and intermediate consumption, and $\boldsymbol{X}^e$ represents outputs for exports including direct goods and indirect products related to production for exports. $\boldsymbol{X}$, $\boldsymbol{X}^e$ and $\boldsymbol{F}$ are vectors representing individual sectors.

In calculating EEE, $\boldsymbol{X}^e$ is derived from official economic data through the IOA (see section 1.2). $\boldsymbol{F}$ is calculated from Eq. 3 sector by sector:

$$F_i = P_i / X_i \qquad (3)$$

Here the sectoral total emission P_i is estimated using a technology-based bottom-up method (9) (see section 1.3). And the sectoral output X_i is derived from the IOA (see section 1.2).

Emissions associated with imports are more complicated than those for exports. They are characterized by emissions avoided by imports (EAI) and emissions embodied in imports (EEI). EAI are defined as the additional emissions that China would have produced if all Chinese imports had been made domestically:

$$\text{EAI} = \boldsymbol{F} \cdot \boldsymbol{X}^m \qquad (4)$$

where $\boldsymbol{X^m}$ represents the associated outputs. An implicit assumption here is that China, with its existing technology and supply chain, is capable of manufacturing all products obtained currently from abroad. By comparison, EEI are emissions in trade partners due to production of goods exported to China. EEI and EAI differ mainly as a result of differences in emission intensity between China and its trade partners. Both quantities are analyzed in the present study. Differences between EEI and EEE represent the gap between consumption-based Chinese emissions and production-based Chinese emissions (6).

1.1.1 Calculation of emissions embodied in imports (EEI)

Production processes in China are, on average, more emission-intensive compared to its trade partners. Averaged over the world, 0.74 kg of CO_2 are emitted in 2006 for one U.S. Dollar of gross domestic production (GDP; using prices in 2000), compared to the value for China at 2.45 kg CO_2 per U.S. Dollar (12), resulting in a ratio of 3.3 for Chinese to world average emissions per GDP (Table S1). Ratios for individual countries can be found in Table S1.

EEI for CO_2 are calculated as EAI adjusted by emission/GDP of China relative to those of trade partners:

$$\mathrm{EEI_i = EAI_i} \cdot \frac{\mathrm{(Emission/GDP)_i}}{\mathrm{(Emission/GDP)_{China}}} \qquad (5)$$

where i represents a given trade partner. GDP data for all trade partners are taken from the World Bank (http://data.worldbank.org/) and CO_2 emissions from the International Energy Agency (IEA; http://www.iea.org/). Here potential differences are neglected in energy structure and industrial supply chain between production for domestic consumption and production for exports. Specifically, the amount of energy needed to produce a domestically consumed product is assumed to be the same as that for exports.

A similar approach is used to calculate EEI of short-lived pollutants (Eq. 5). Global emissions of SO_2, NOx and CO are taken from EDGAR v4.2

(http://edgar.jrc.ec.europa.eu/overview.php?v=42) with emissions in selected regions replaced by respective regional inventories: this study for Chinese emissions, NEI05 (http://www.epa.gov/ttnchie1/trends/) for the U.S., EMEP (13) for European Union (EU), and REAS (14) for Japan. Emissions of BC and OC outside China are taken from Bond et al. (15) and are remained constant over 2000 – 2009 in lack of information.

A multi-regional input-output model (6, 16) is an alternate approach to derive EEI of China, as has been employed for calculating CO_2 emissions. The multi-regional approach accounts for the global supply chain of a final product, compared to our method that considers bilateral trade. A multi-regional IOA is much more difficult for air pollutants since it requires detailed information regarding emission factors that vary considerably across the countries, sectors, industrial processes/technologies and emission control technologies. Thus the multi-regional IOA can be done only for limited years and trade partners with adequate economic statistics and emission factor information, not allowing for evaluating the interannual variability. It is not adopted for the present study. As shown in section 5.2.4, EEI of CO_2 derived here are close to the estimate by Peters et al. (6) using a multi-regional IOA, with a small difference of about 10% averaged over 2002 – 2008. Additional errors are added in uncertainty analysis in section 5 to account for the simplified conversion from EAI to EEI here.

1.2 Input-output analysis: Derivation of $\boldsymbol{X}$, $\boldsymbol{X^e}$ and $\boldsymbol{X^m}$

The IOA is used to calculate $\boldsymbol{X}$, $\boldsymbol{X^e}$ and $\boldsymbol{X^m}$. Based on the Handbook of Input-Output Table Compilation and Analysis (3), the standard input-output model is defined as follows:

$$\boldsymbol{X} = \mathbf{A}\boldsymbol{X} + \boldsymbol{Y} \qquad (6)$$

Here $\boldsymbol{Y}$ represents the net final demand, i.e., final consumption and exports less imports, and $\mathbf{A}\boldsymbol{X}$ denotes the intermediate consumption. $\mathbf{A}$ is a direct requirement coefficient matrix whose element A_{ij} denotes the amount of product from industry i required to produce a given unit of product from industry j. Thus the total outputs $\boldsymbol{X}$ can be represented as:

$$\boldsymbol{X} = (\mathbf{I} - \mathbf{A})^{-1}\boldsymbol{Y} \qquad (7)$$

where $\mathbf{I}$ denotes the unity matrix.

The net final demand $\boldsymbol{Y}$ can be broken into several components:

$$\boldsymbol{Y} = \boldsymbol{C} + \boldsymbol{E} - \boldsymbol{M} = \boldsymbol{C}^{d} + \boldsymbol{C}^{m} + \boldsymbol{E} - \boldsymbol{M} \qquad (8)$$

where $\boldsymbol{C} = \boldsymbol{C}^{d} + \boldsymbol{C}^{m}$ is the final consumption including domestically-produced final consumption ($\boldsymbol{C}^{d}$) and imported final consumption ($\boldsymbol{C}^{m}$), $\boldsymbol{E}$ represents exports, and $\boldsymbol{M}$ represents imports.

The sectoral vector $\mathbf{A}\boldsymbol{X}$ represents total intermediate consumption including products supplied domestically, $\mathbf{A}^{\mathbf{d}}\boldsymbol{X}$, and products supplied by import partners (which are unrelated to EEE), $\mathbf{A}^{\mathbf{m}}\boldsymbol{X}$.

Therefore Eq. 6 can be expressed as:

$$\begin{aligned}\boldsymbol{X} &= (\mathbf{A}^{\mathbf{d}} + \mathbf{A}^{\mathbf{m}})\boldsymbol{X} + \boldsymbol{C}^{d} + \boldsymbol{C}^{m} + \boldsymbol{E} - \boldsymbol{M} \\ &= \mathbf{A}^{\mathbf{d}}\boldsymbol{X} + \boldsymbol{C}^{d} + \boldsymbol{E} + (\mathbf{A}^{\mathbf{m}}\boldsymbol{X} + \boldsymbol{C}^{m} - \boldsymbol{M})\end{aligned} \qquad (9)$$

Imports $\boldsymbol{M}$ are used for final consumption ($\boldsymbol{C}^{m}$) and intermediate consumption ($\mathbf{A}^{\mathbf{m}}\boldsymbol{X}$) (3):

$$\boldsymbol{M} = \mathbf{A}^{\mathbf{m}}\boldsymbol{X} + \boldsymbol{C}^{m} \qquad (10)$$

Thus

$$\boldsymbol{X} = \mathbf{A}^{\mathbf{d}}\boldsymbol{X} + \boldsymbol{C}^{d} + \boldsymbol{E} \qquad (11)$$

Therefore

$$\begin{aligned} \boldsymbol{X} &= (\mathbf{I}-\mathbf{A^d})^{-1}(\boldsymbol{C^d}+\boldsymbol{E}) \\ &= (\mathbf{I}-\mathbf{A^d})^{-1}\boldsymbol{C^d}+(\mathbf{I}-\mathbf{A^d})^{-1}\boldsymbol{E} \\ &= \boldsymbol{X^d}+\boldsymbol{X^e} \end{aligned} \tag{12}$$

It is thus clear that $\boldsymbol{X}$ consists of the outputs for domestic consumption, $\boldsymbol{X^d}$, and the outputs for exports, $\boldsymbol{X^d}$:

$$\boldsymbol{X^d} = (\mathbf{I}-\mathbf{A^d})^{-1}\boldsymbol{C^d} \tag{13}$$

$$\boldsymbol{X^e} = (\mathbf{I}-\mathbf{A^d})^{-1}\boldsymbol{E} \tag{14}$$

Based on the above analysis, EEE can be derived as

$$\text{EEE} = \boldsymbol{F}\cdot\boldsymbol{X^e} = \boldsymbol{F}\cdot(\mathbf{I}-\mathbf{A^d})^{-1}\cdot\boldsymbol{E} \tag{15}$$

Assuming that the technology and supply chain embedded in imported goods is the same as that for goods produced domestically, $\boldsymbol{X^m}$ can be derived as follows:

$$\boldsymbol{X^m} = (\mathbf{I}-\mathbf{A^d})^{-1}\boldsymbol{M} \tag{16}$$

Therefore

$$\text{EAI} = \boldsymbol{F}\cdot(\mathbf{I}-\mathbf{A^d})^{-1}\cdot\boldsymbol{M} \tag{17}$$

In calculating EEE and EAI, $\boldsymbol{E}$ and $\boldsymbol{M}$ are derived from the China Trade and External Economic Statistical Yearbook for 2001 – 2010 (11). The calculation of $\mathrm{A^d}$ is detailed below.

1.2.1 Calculation of A^d

Each element of the matrix $\mathrm{A^d}$ is the portion of $\mathrm{A_{ij}}$ supplied by domestic producers:

$$\mathrm{A^d_{ij}} = \mathrm{R_{ij}}\cdot\mathrm{A_{ij}} \tag{18}$$

In lack of detailed information on $\mathrm{R_{ij}}$, a common assumption is adopted in this study (4, 5, 17): While the products of a given industry i may be imported or produced domestically, all industries that need the products have the same import ratio; thus j is irrelevant. Then R_{ij} can be expressed as:

$$\mathrm{R}_{ij} = 1 - \frac{M_i}{X_i + M_i - E_i} \qquad (19)$$

where M_i represents the import volume of products from industry i, and $X_i + M_i - E_i$ represents the amount of products consumed domestically.

1.3 Derivation of sectoral emission inventory for China

Several emission inventories have been derived for CO_2 and air pollutants in China (9, 10, 12, 18). These inventories are specified normally for several major sectors (namely power plants, industry, transportation and residential use), the number of which is inadequate for direct use in a detailed IOA for later calculation of sectoral emission intensity. In addition, existing inventories do not cover the whole period of 2000 – 2009 for all species. Therefore a yearly varying emission inventory over 2000 – 2009 is developed in this study for a total of 42 sectors corresponding to the IOA (see Table S2).

Emissions of CO_2 are derived from fuel combustion and industrial processes. They are estimated using the IPCC Tier 1 approach (19).

For air pollutants, emission factors vary significantly across the technologies in combustion, industrial processes and associated control measures. From 2000 to 2009, new technologies were coming rapidly into Chinese marketplace. Therefore a technology-based approach is adopted here to account for variations in technology and resulting emission factors, following Streets et al. (9) and Zhang et al. (10).

1.3.1 Calculation of emission factors for air pollutants

Emissions from stationary combustion and off-road mobile sources are estimated as (10):

$$E_i = \sum_j AC_{ij} \cdot (\sum_k FR_{ijk} \cdot EF_{jk}) \qquad (20)$$

where i denotes the sector, j the type of fuel or product, and k the type of technology in combustion or industrial processes. AC represents the activity rate, FR the penetration rate of a given technology, and EF the corresponding emission factor. Here fuels are assumed to be combusted in boilers except for the major industrial processes listed in Table S3. Data sources are discussed in sections 1.4.2 and 1.4.3 for activity rates, technology penetration and emission factors.

Emissions from on-road vehicles are calculated as follows (10):

$$E_{tr} = \sum_j (VP_j \cdot VM_j \cdot FE_j \cdot EF_j) \qquad (21)$$

where j denotes the vehicle type. VP represents the vehicle population, VM the annual average vehicle mileage traveled (in km/year), FE the average fuel economy (in kg/km), $VP \cdot VM \cdot FE$ the fuel consumption, and EF the emission factor (in g/kg). The data sources are specified in section 1.4.

For a given technology of stationary or transportation sources, the emission factor is estimated as follows:

$$EF = EF_{raw} \cdot \sum_n C_n \cdot (1-\eta_n) \qquad (22)$$

where n denotes the type of control technology. EF_{raw} represents the unabated emission factor, C the penetration rate of a given control technology, and η the removal efficiency of the control technology.

Emissions of sulfur dioxide (SO_2) are derived mostly from combustion of fuels containing sulfur. Thus the emission factors can be calculated as:

$$EF_{raw,SO_2} = 2 \cdot S \cdot (1\text{-}SR) \qquad (23)$$

where S represents the sulfur content in the fuel, and SR the sulfur retention in the ash. S and SR are specified in section 1.4.3. For industrial non-combustion processes, emission factors are derived from GAINS-Asia (20) and Lei et al. (21).

2. Data sources

2.1 Input-output tables

To calculate $\boldsymbol{X}$, $\boldsymbol{X^e}$ and $\boldsymbol{X^m}$, this study uses official input-output tables (IOTs) for 2000, 2002, 2005 and 2007 from the Chinese National Bureau of Statistics (11, 22). The IOTs contain 42 sectors for 2002, 2005 and 2007 but only 17 sectors for 2000 (see below).

Interpolation is implemented to estimate IOTs for other years with no official IOT statistics, i.e., the coefficient A_{ij} is interpolated linearly to target years. This procedure is important considering the rapidly changing industrial and trade structure of China over 2000 – 2009 (11) (see Fig. S2). Before 2004, China was a net importer of steels and irons whose production is energy-intensive, and it at the same time produced a large number of labor-intensive products such as furniture, toys and clothes for both domestic consumption and exports. Starting from 2004, however, China has gradually transitioned to be a major exporter of steels, irons and other energy-intensive industrial products, resulting in reduced contribution of labor-intensive industries in the economic structure. As a demonstration, EEE of CO_2 in 2004 would be estimated at 1301 Tg based on the IOT of 2002, about 15% lower than if the IOT of 2005 was used.

The RAS method (see the Handbook of Input-Output Table Compilation and Analysis (3)) was suggested as a plausible approach to derive IOTs for years without official IOT statistics. It was however not suitable for China due to lack of critical data (23). Here the RAS method is compared to the interpolation approach. In particular, the official IOT for 2005 is used to evaluate the IOT generated from 2002 through the RAS method and the IOT interpolated from 2002 and 2007. Errors are less than 25% for most coefficients (A_{ij}) based on the interpolation approach, but are larger than 50% for half of the coefficients using the RAS method. Therefore interpolation seems to be a more appropriate approach for our input-output analysis.

Note that the official IOT of 2000 contains 17 sectors only. In deriving the IOT of 2001, the IOT of 2002 is mapped to the same 17 sectors (Table S4) and employed then with the IOT of 2000 for interpolation. Furthermore, the IOT of 2007 is applied directly to 2008 and 2009 in lack of necessary official statistics.

2.2 Activity rates

Activity rates of China are collected for 2000 – 2009 from a wide variety of sources, as summarized in Table S5.

For stationary and off-road mobile sources, data are obtained for sectoral fuel consumption from the national final energy consumption table of the Chinese Energy Statistical Yearbook consisting of 45 categories (24). Some inconsistency has been revealed in energy and emission activity data between national-level and provincial-level statistics (25, 26). In lack of additional information regarding the accuracy of these statistics, the national-level data are employed in the present study together with an uncertainty analysis partially accounting for this issue. The energy data are mapped to 42 categories to match the IOTs (see Table S2).

For the industrial sector, quantities of industrial products are taken from the China Statistical Yearbook (11), the China Iron and Steel Statistics (27) and China Cement Almanac (28).

In calculating emissions from transportation, vehicles are classified into light-duty gasoline vehicles (LDGV), heavy-duty gasoline vehicles (HDGC), diesel vehicles (DV) and motorcycles. Data for vehicle population (VP) are taken from the China vehicle emission control annual report (29). Fuel economy (FE) data are obtained from Streets et al. (30, 31) for individual vehicle types. Data for annual average vehicle mileage traveled (VM) are derived from the Year Book of China Transportation and Communications (32) based on the approach by He et al. (31).

2.3 Emission factors

Emission factors for CO_2 are documented in the revised 1996 IPCC guidelines for national greenhouse gas inventories (19).

For air pollutants, emission factors are taken from the literature with preference for results from domestic measurements and/or from more recent studies. Results for foreign countries in line with the current technology level in China are used when domestic information is not available. Data are summarized in Table S6.

(a) SO_2

The sulfur content in fuels (S) is derived from various studies (14, 18, 20, 33). Averaged over China, S in coal differs insignificantly between 2000 (1.08%) and 2005 (1.02%); and linear interpolation is implemented to obtain values for 2001 – 2004. After 2005, a value of 1.02% is used in lack of additional information. Emission factors for other fuel types are collected from the Greenhouse Gas-Air Pollution Interactions and Synergie-China (GAINS-China (20)) model.

Information for sulfur retention in the ash (SR) is taken from Lu et al. (18). SR is set at 10% for coal-fired power plants, and varies from 5% to 45% for other sectors depending on the combustion technology and fuel type.

The removal efficiency of flue-gas desulfurization (FGD) systems equipped in power plants can reach 95% in theory(34). However, the actual efficiency was much smaller prior to 2007 because of low operation rates (35). Since 2007, the efficiency may exceed 90% due to a series of changes in environmental legislation enforcing the implementation of FGD (36) (in part by forcing to replace small and highly-emitting plants with larger and cleaner ones with FGD systems (37)). Overall, the Ministry of Environmental Protection of the People's Republic of China (MEP) reported that 73.2 % of SO_2 was removed from coal-fired power plants equipped with FGD in 2007 (38). Following Lu et al. (18), a triangular distribution function is built in this study to estimate the actual efficiency, by using the official data (38) as the most plausible values and the value of 95% as the maximum.

(b) Nitrogen oxides (NO_x)

As analyzed in detail by Zhang et al.(25) and Lin et al. (37), there exist three new technologies in China with significant influences on emission factors of NO_x: (1) low-NO_x burner technology (LNB) in power plants, (2) precalciner kilns in the cement industry, and (3) emission control technologies in vehicles. Since 2007, the rapid penetration of fluidized-bed furnaces also has large impacts on NO_x emissions in industrial boilers.

Emission factors are taken from Zhang et al. (10, 25) for the power and transportation sectors in 2000 – 2004 and 2006. Emission factors for 2005 are interpolated from 2004 and 2006. Values for 2006 are applied to later years in lack of additional information. Overall, the national average emission factor in power plants declined from 8.0 g/kg-coal in 2000 and 2001 to 7.1 g/kg-coal in 2006 and to 6.85 g/kg-coal in 2009 due to the increasing fraction of LNB boilers. Emission factors for gasoline vehicles are likely overestimated over 2007 – 2009 since improvements in emission standards are not taken into account.

Emission factors for non-cement industries are derived from Zhang et al. (10) for 2000 – 2006 and from the China Electrical Equipment Industrial Association for 2007 – 2009. Emission factors of 3.8, 4.0 and 8 g/kg-coal are used for hand-feed stokers, automatic stokers and fluidized-bed furnaces, respectively. The technology distribution of these industrial boilers remains relatively stable from 2000 to 2006. After 2006, the distribution of fluidized-bed furnaces increased rapidly, from 13.6% in 2007 to 21.8% in 2009. By 2009, the average emission factor for industrial boilers was larger than the 2000 level by 10%.

For cement industry, emission factors are adopted from Lei et al. (21) to account for the rapid change in the use of two main types of kilns in China: shaft kilns and rotary kilns. Shaft kilns are smaller and easier to construct, while rotary kilns have higher productivity and efficiency with a higher emission factor for NO_x. Precalciner (new-dry) kilns, a special type of rotary kilns, have an emission factor of 15.3

g/kg-coal, about nine times as large as the value of 1.7 g/kg-coal for shaft kilns. Precalciner kilns have been employed rapidly in recent years to replace small shaft kilns which used to contribute 80% of total cement production. By 2008, more than 60% of cement was produced from precalciner kilns (21).

(c) Carbon monoxide (CO)

Emission factors for CO are taken from Streets et al. (30) and Zhang et al. (10). They are about 2 and 8 g/kg-coal for pulverized boilers and automatic stokers, respectively, in power/heating devices, and range from 2 to 124 g/kg-coal for industrial boilers (see Table S3).

From 2000 to 2009, new iron and steel factories were built massively with increased by-pass gas recycling and thus reduced CO emission factors. As a result, CO emission factors declined from 59.0 g/kg-iron in 2001 to 39.6 g/kg-iron in 2006 for iron production, and from 37.0 g/kg-steel in 2006 to 24.0 g/kg-steel in 2001 for steel production.

For the cement industry, emission factors are taken to be 155.7 g/kg-coal for shaft kilns because of low combustion efficiency, and are only 17.8 g/kg-coal for rotary kilns. The average emission factor in cement production has decreased significantly in recent years due to the promotion of precalciner kilns.

For the transportation sector, emission factors vary from 5 to 156 g/km depending on vehicle and fuel types (30). Similar to NO_x, CO emissions from gasoline vehicles are likely overestimated over 2007 – 2009 by not accounting for recent progress in emission standards and implementation.

(d) Black carbon (BC) and organic carbon (OC)

Emission factors for BC and OC are adopted from Lu et al. (18) that is based on Bond et al. (39) and takes into account changes during the past ten years.

2.4 Economic data

Calculation of emission intensity requires information about the sectoral total outputs $\boldsymbol{X}$, which can be derived year by year based on the IOA and the final consumption ($\boldsymbol{Y}$) using Eq. 7.

For a given year, the sum of final consumption from all sectors, $\sum_i Y_i$, is proportional to GDP:

$$
\begin{aligned}
\text{GDP} &= \text{Total industrial output - Total industrial intermediate consumption+} \\
&\quad \text{Taxes less subsides on products} \\
&= \sum_i X_i - \sum_i (\mathrm{A}X)_i + \text{Taxes less subsides on products} \qquad (24) \\
&\approx (1+\text{Rate of taxes less subsides})[\sum_i X_i - \sum_i (\mathrm{A}X)_i] \\
&= (1+\text{Rate of taxes less subsides})(\sum_i Y_i)
\end{aligned}
$$

where i denotes the sector. China joined the World Trade Organization (WTO) in 2001, since when its tax and subsidy rates remained relatively stable until 2008 (http://www.taxrates.cc/html/china-tax-rates-html). Therefore interannual variation of $\sum_i Y_i$ can be derived from Eq. 24, with GDP data from 2000 to 2009 taken from the China Statistical Yearbook (11). Furthermore, detailed information about Y_i is available for 2002, 2005 and 2007 (22). Such information is employed then to interpolate the contribution of individual sectors to total final consumption ($\sum_i Y_i$) for other years.

Exports ($\boldsymbol{E}$) and imports ($\boldsymbol{M}$) are taken from the China Trade and External Economic Statistical Yearbook for 2001 through 2010 (40). Since 1992, China has utilized a harmonized coding system to code, classify, and conduct statistical analyses for import and export commodities. The coding system includes information for 22 sections and 98 chapters, which is projected here to the 42 sectors for IOA (see Table S7).

Figure S2a presents GDP, export and import volumes of China from 2000 to 2009 needed for emission analysis.

3. Monte Carlo method for uncertainty evaluation

As evident from the analysis above, the calculation EEE and EAI is subject to errors of varying magnitudes in emission factors, activity rates, IOTs, and other economic data. The resulting emission uncertainties are estimated using the Monte Carlo approach with at least 10,000 simulations for any given species depending on the convergence efficiency. For EEI, additional errors are incorporated in uncertainty analysis upon results from the Monte Carlo simulations to account for the simplified conversion from EAI to EEI in the present study (see section 5).

A critical procedure of Monte Carlo simulations is specifying probability distributions of errors in individual input parameters. Based on a review of previous studies, errors in most parameters are assumed to follow zero-mean normal distributions, except for emission factors of BC and OC for which a lognormal distribution is adopted (18).

Errors in each element of $\mathbf{A}$ (A_{ij}) are assumed to have a 95% confidence interval (CI) of [-10%, 10%] (relative to A_{ij}) for 2000, 2002, 2005 and 2007. For other years with no direct official data, errors from interpolation shown in section 1.4.1 are added (in quadrature) to account for the impact of rapidly changing industrial structure.

Errors in export and import volumes are assumed to have a CI of [-10%, 10%], since they have been reorganized to match the sectors in the IOTs. The CI of errors in GDP data is assigned to be [-5%, 5%].

For errors in fossil fuel consumption data, the CI is set at [-10%, 10%] for power plants, [-20%, 20%] for the industrial sector and residential liquid fuel use, and [-33%, 33%] for residential coal use (34). The error assignment accounts for differences between the national-level (used here) and the provincial-level economic statistics. The CI is taken to be [-15%, 15%] and [-30%, 30%] for errors in VP and VM, respectively.

The CI of errors in emission factors is set at [-10%, 10%] for CO_2, [-20%, 20%] for SO_2, [-30%, 30%] for NO_x and [-70%, 70%] for CO (9, 10). For emission factors of BC and OC, lognormal distributions are adopted here with uncertainty estimates following Lu et al. (18) for individual sectors.

4. Total emissions in China

Figure S3 shows the trend of total emissions in China from 2000 to 2009 for four main sectors: power plants, industry, transportation and residential use.

In China, CO_2 emissions are derived mainly from coal and oil combustion in the power and industrial sectors, with a minor contribution from natural gas usage. As shown in Fig. S3, CO_2 emissions increased from 2000 to 2009 at a rate of about 9% per year along with the economic booming and resulting growth in energy consumption (12). Our results are slightly larger than the IEA estimate (12). The differences are less than 5% throughout the years, and are attributed mainly to the industrial sector. A likely factor is use of oils in the refinery industry assumed here to be combusted due to lack of detailed information.

Trend of SO_2 emissions differs between two time periods (Fig. S3). From 2000 to 2006, emissions increased dramatically as a result of the rapidly increasing energy consumption and coal use. After 2006, SO_2 emissions began to decrease resulting primarily from the application of FGD systems, the phase-out of small and highly-emitting power generation units, and the economic recession (section 1.4.3). The FGD systems alone have reduced emission factors in power plants by about 69% from 2000 to 2009. Our results are within 10% of Zhang et al. (10) and Lu et al. (18). Note that the national-level statistics are employed here for activity rates, differing from the provincial-level data used by Zhang et al. (10).

Emissions of NO_x increased rapidly from 2000 to 2008 (averaged at 8.4% per year; see Fig. S3), with an increment by 26% from 2005 to 2008 close to constraints from satellite measurements at 27-33% (41). The growth is driven mainly by explosive growth in the power and industrial sectors and the use of precalciner kilns for cement production with high emission factors (10). The rapidly increasing penetration of fluidized-bed furnaces since 2007 also had a large impact on NO_x emissions from industrial boilers. Emissions in the transportation sector grew slowly because of the rapidly expanding vehicle fleet compensated substantially by the effect of continuously enhanced vehicle emission standards (25, 37). After 2008, emission growth slowed down mainly reflecting the global financial crisis (37, 41). The amount of emissions for 2006 is about 20% lower than the constraint from satellite measurements (42) due to errors in the bottom-up calculation and/or errors embedded in the satellite-based constraint process (25, 43). Vehicle emissions are likely overestimated over 2007 – 2009 since emission factors are fixed at the 2006 level in lack of further information.

CO is emitted mainly from industrial combustion, residential burning and vehicle exhaust with relatively low combustion efficiency. Emissions of CO increased at a relatively slow pace of 5% per year from 2000 to 2005 (Fig. S3), despite the rapid economic and industrial development. This is in part because of the increasing penetration of precalciner kilns with much smaller emission factors than previously dominant shaft kilns. Other factors include the increasing new combustion boilers with by-pass gas recycling devices and new iron/steel factories with lower emission factors in the non-combustion processes (see section 1.4.3 and Table S5). In the residential sector, emissions of CO were relatively stable over the years due to reductions in emission factors compensated by enhancements in activity rates. CO emissions declined slightly since 2006 in the transportation sector. Overall, our results are lower than Zhang et al. (10) by about 13% in 2001 and 3% in 2006.

BC is produced mostly from incomplete combustion in small and low-temperature facilities. The residential sector contributes about 49-55% of BC emissions in China across the years (Fig. S3). Overall, BC emissions increased slightly from 2000 to 2009, in close agreement with Lu et al. (18) with differences less than 5% for individual years. The trend is determined by increasing activity rates compensated in part by decreasing emission factors. From 2000 to 2008, GDP grew by 177% while emission factors for industrial and residential coal use decreased by 64% and 34% for the same period, respectively (18).

OC exhibited an emission trend similar to BC. As the dominant source, the residential sector accounted for 72 – 79% of OC emissions during 2000 – 2009. Throughout the years, the contribution increased from the transportation sector and decreased from the industrial sector, as a result of increasing vehicle numbers concurrent with decreasing emission factors in industrial coal use. The estimate here is close to Lu et al. (18) with differences less than 10% for all years.

5. Emission intensity and trade-induced emissions

5.1 Emission intensity

Emission intensity ($\boldsymbol{F}$) in 2002, 2005 and 2007 are shown in Tables S8-9 for CO_2 and air pollutants from various sectors. Among the non-residential sectors, emissions are most intensive in the electricity/heating/water industry, building materials and non-metal mineral products industry, transportation and metal products industry.

Note that the calculation of emission intensity is affected by the use of economic outputs in monetary units subject to inflation over the years. The effect is partially accounted for by using the PPI for inflation adjustment. Furthermore, $\boldsymbol{F}$ is an intermediate term in deriving trade-related emissions (EEE=$\sum_i F_i X_i^e = \sum_i (P_i X_i^e / X_i)$ and EAI=$\sum_i F_i X_i^m = \sum_i (P_i X_i^m / X_i)$, where both $\boldsymbol{X^e}$ and $\boldsymbol{X^m}$ are affected by inflation), thus the inflation-induced uncertainties likely have an insignificant impact on trade-related emissions.

5.2. Trade-induced emissions

5.2.1 Emissions embodied in exports (EEE)

Figure S5 presents EEE of CO_2 and air pollutants from 2000 to 2009. For all species, EEE increased dramatically from 2001 to 2007 as a result of increasing $\boldsymbol{X}^e$ by a factor of about four (Fig. S2). Since 2007, EEE reduced generally because both of decreasing $\boldsymbol{X}^e$ associated with the global final crisis (Fig. S2) and of decreasing emission intensity due to technology development and environmental legislation (see sections 2.3 and 3).

Figure S5 also specifies emissions embodied in exports to the U.S., European Union (EU), Japan, and the rest countries. For a given year, the fractions of EEE attributable to exports to a particular trade partner were relatively consistent among the species. Exports to the U.S. accounted for 21% of the total EEE over 2000 – 2007. The portion for EU increased from 16% in 2000 to 20% in 2007. The contributions of exports to the U.S. and EU declined in 2008 and 2009 as a result of the financial crisis and shrinking demand. Japan accounted for about 15% of the total EEE during 2000 – 2003, reducing since to about 7% in 2009. For all species, the three regions accounted for half of the EEE and almost 15% of total emissions in China for CO_2 and SO_2.

5.2.2 CO_2 emissions embodied in exports (EEE) and comparison with previous studies

EEE of CO_2 increased from 697 Tg in 2001 to 2283 Tg in 2007 (by a factor of 328%) and then declined rapidly to 1608 Tg by 2009, primarily as a result of the varying $\boldsymbol{X}^e$. Meanwhile, the emission intensity of CO_2 was relatively stable over the years (see Tables S8-9).

Figure S4a compares our results with Weber et al. (17), Liu et al. (44) and Peters et al. (6). Unlike other studies, Liu et al. (44) did not use the IOA approach. Rather, they calculated the EEE by multiplying the export values by the average emission intensity. Our results are slightly higher than Peters et al. (6), especially after 2004. This is mainly because of the rapid structural changes in supply chain explicitly taken into account here. Peters et al. (6) employed the IOT of 2002 adopted from the Global

Trade Analysis Project 7 (GTAP-7) to calculate the EEE during 2003 – 2008. Here a test is conducted to estimate the EEE for 2000 – 2009 using the IOT of 2002, resulting in emissions similar to Peters et al. (6).

Figure S4b further compares emissions embodied in Chinese exports to the U.S. (EEE-U.S.) to previous estimates by Peters et al. (6), Shui et al. (45) and Du et al. (46). Our results are consistent with Peters et al. (6), especially when accounting for the structural change in supply chain considered here. Results from Shui et al. (45) are much larger due primarily to the use of different export data (Fig. S4b). Shui et al. (45) employed data from the U.S. Census Bureau providing much higher values than the Chinese National Bureau of Statistics adopted here. Based on the U.S. dataset, Chinese exports amounted to 102.280 billion USD in 2001, about 90% higher than the Chinese statistics. The discrepancy is attributed to the different official definitions of exports and imports, particularly when accounting for Chinese exports to the U.S. via a third party. If the U.S. statistics were used here, our results would be close to Shui et al. (45) in 2000 – 2001 with some remaining differences in 2002 – 2003 for reasons that are currently unclear (see Fig. S4b). Du et al. (46) used the same economic statistics as the present study but suggested EEE-U.S. to be about twice as much as our results and Peters et al. (6). According to Du et al. (46), EEE-U.S. accounted for about 12% of total Chinese emissions in 2007, implying a value of 6721 Tg for total emissions that is about 10% higher than the IEA estimate (12) and about 8% higher than our results. This however cannot fully explain the large differences in EEE-U.S. and warrant further investigation.

5.2.3 Air pollutants embodied in exports (EEE)

As shown in Fig. S5, EEE of SO_2 increased from 4.8 Tg in 2001 to 12.4 Tg in 2006 (by a factor of 257%) with a slight increase from 2006 to 2007. The rate of increase is smaller than CO_2 attributed mainly to the dramatically decreasing emission intensity after 2004 with the implementation of FGD systems (Table S8). After 2007, EEE of SO_2 declined due to continuously decreasing emission intensity accompanied by declining exports.

EEE of NO_x increased from 2.2 Tg in 2000 to 7.1 Tg in 2007 (by a factor of 322%), close to the trend of EEE of CO_2. The growth was driven mainly by the economic and industrial growth. Although emission intensity of NO_x increased rapidly in the building materials and non-metal products industries, these sectors serve dominantly for domestic use with a lesser influence on export-related emissions. For the power and transportation sectors, emission intensity of NO_x declined faster than that for CO_2 due to installation of LNBs and vehicle emission control technologies, respectively. After 2007, EEE of NO_x declined along with decreasing exports.

For CO, EEE increased from 14.4 Tg in 2001 to 39.7 Tg in 2007 (by a factor of 280%), at a rate lower than CO_2 due to rapidly decreasing emission intensity (Table S8). After 2007, reductions in emission intensity and exports resulted in significant declines of EEE with a total of only 24.9 Tg in 2009.

For BC and OC, residential use is the main emission source and is relatively independent of exports. In other sectors, emission intensity decreased significantly over the years, partially compensating for the effect of rapidly growing export volume. As a result, EEE of BC and OC increased from 2001 to 2007 at a rate smaller than other species. For BC, EEE increased continuously from 125 Gg in 2001 to 291 Gg in 2007 and then declined gradually to a value of 187 Gg in 2009. EEE of OC exhibited a similar trend.

5.2.4 Emissions avoided by imports (EAI) and emission embodied in imports (EEI)

During 2000 – 2009, China imported large quantities of machines, equipment, chemical/metal products, and other goods. As shown in Fig. S2, the sectoral sum of $\boldsymbol{X^m}$ continued to grow until disrupted by the global recession in 2008 – 2009. There was a sharp increase between 2002 and 2004 mainly because of enhanced imports of iron, steels and other industrial materials.

Between 2000 and 2002, EAI were relatively stable for most species (Fig. S5) as a result of slowly increasing $\boldsymbol{X^m}$ (Fig. S2) compensated by slowly decreasing emission intensity (Tables S8-9). In the following two years, increases in $\boldsymbol{X^m}$

(particularly in the steel, iron and coke industries) overcompensated for the effect of declining emission intensity, resulting in rapid growth of EAI. From 2005 to 2007, EAI decreased gradually for SO_2, BC, OC and CO due to reductions in emission intensity outweighing the effect of increasing import volume (Fig. S5). On the contrary, EAI for CO_2 and NO_x increased gradually since the emission intensity declined more slowly. After 2007, both $\boldsymbol{X}^{m}$ and $\boldsymbol{F}$ decreased (Fig. S2 and Tables S8-9) resulting in sharp decline of EAI for all species.

The fractions of EAI with respect to individual trade partners are similar for all species. Japan accounted for 21% of EAI in 2000 decreasing gradually to 16% in 2009. The U.S. and EU contributed 8% and 13%, respectively, averaged over the years.

EEI are lower than EAI by a factor of 3 – 5 during 2000-2009 (Fig. S5) reflecting the high emission/GDP ratio of China relative to its trade partners on average (Table S1). EEI of CO_2 derived here are close to the multi-regional IOA estimate by Peters et al. (6) with a small difference of about 10% averaged over 2002 – 2008.

The U.S., EU and Japan each contributed about 6% to EEI of CO_2 averaged over the years. Their total contribution (18%) was about half as much as that for EAI. For air pollutants, the fractions of EEI with respect to individual trade partners vary across the species due to differences in the emission/GDP ratio (Table S1). Japan, EU and the U.S. together accounted for 13% of EEI for NO_x and 4 – 8% for other species.

Difference between production-based Chinese anthropogenic emissions and consumption-based emissions are calculated as EEE subtracted by EEI (6). This quantity is presented in the main text as the emissions embodied in trade (EET).

5.3 Uncertainties in total and trade-induced emissions

Averaged over 2000 – 2009, the Monte Carlo simulations suggest uncertainties in total emissions (relative to a 95% confidence interval) for CO_2, SO_2, NO_x, CO, BC and OC to be -15% to 15%, -19% to 19%, -31% to 31%, -64% to 64%, -40 % to 80% and -41% to 90%, respectively. Uncertainties are asymmetric for BC and OC, reflecting the assumed lognormal distribution for errors in emission factors (18, 39).

Averaged over the years, uncertainties in EEE of CO_2, SO_2, NO_x, CO, BC, and OC are estimated to be -15% to 15%, -17% to 17%, -27% to 27%, -45% to 45%, -35 % to 51%, -41% to 60%, respectively. They are smaller than those for total emissions because of the weaker influence from the residential sector that is subject to much larger errors than other source types.

Uncertainties for EAI are similar to EEE. For EEI, emissions for CO_2 differ from Peters et al. (6) by ~ 10% averaged over 2002 – 2008 (Fig. S4), which amount is added (in quadrature), in deriving the overall uncertainty here, to account for errors induced by the analysis based mainly on Chinese data instead of performing a multi-regional input-output calculation (section 1.1.1). For air pollutants, an additional error at 50% (instead of 10% as for CO_2) is assumed concerning differences in the effect of economic structure and technology level between CO_2 and air pollutants as well as interannual variability in emission intensity of China relative to that of other countries. The resulting total uncertainty ranges from 52% to 74% for various pollutants (Table S10).

6. GEOS-Chem simulations to analyze impacts of international trade on global atmospheric environment

The international trade, including both exports and imports, has significant consequences on air quality in China and downwind regions. The impacts are evaluated in this section through a series of simulations using the GEOS-Chem CTM.

GEOS-Chem (version 8-03-02; http://wiki.seas.harvard.edu/geos-chem/index.php/MainPage) is driven by the assimilated meteorological fields of GEOS-5 taken from the National Aeronautics and Space Administration (NASA) Global Modeling and Assimilation Office (GMAO). It is run with the full O_x−NO_x−CO−VOC−HO_x chemistry and online calculation for various aerosols (sulfate, nitrate, ammonium, BC, OC, sea salt and dust) on the 2.5° long x 2° lat grid with 47 vertical layers. The non-local scheme is used to simulate vertical mixing in the planetary boundary layer (PBL)(47, 48).

Natural emissions are specified in Lin (2012) (42). Global anthropogenic emissions are taken from the EDGAR database, which are replaced by various regional inventories over the U.S. (NEI05; http://www.epa.gov/ttn/chief/net/2005inventory.html#inventorydata), Canada (CAC; http://www.ec.gc.ca/pdb/cac/cac_home_e.cfm), Mexico (BRAVO (49)) and Europe (EMEP (13)). Anthropogenic emissions in Asia are taken from the INTEX-B inventory as representative of 2006 (10) for various species including NO_x, CO, non-methane volatile organic compounds (VOC), SO_2, BC and OC; and the associated seasonal and diurnal variability is described in Lin (2012) (42). Over China, the INTEX-B emissions are replaced by our estimate for the same year for SO_2, NO_x, CO, BC and OC, as detailed below.

Model simulations require information on the spatial and seasonal distributions of emissions from individual sectors. The spatiotemporal distributions of total emissions are available from the INTEX-B dataset (10), specified for four major sectors: power plants, industry, transportation and residential use. Spatial distributions of EEE, EAI and EEI are much more difficult to obtain due to lack of information on source areas of raw/intermediate/final products and domestic transportation related to exports and imports. The seasonality of trade-related emissions is also difficult to derive in lack of relevant economic statistics.

For the power and transportation sectors, differences in spatial distribution are likely small between emissions related to exports and emissions resulting from production/transportation of goods for domestic consumption. Spatial differences are larger for the industrial sector since the industrial outputs in some regions may rely more on export demand than those in other regions. In lack of detailed information, it is assumed here that EEE exhibit the same spatial distribution as total emissions specified in the INTEX-B dataset. Similar assumptions are implemented for the seasonality of EEE and for the spatiotemporal distributions of EAI and EEI. Further research is required to better constrain the spatiotemporal variability of trade-induced emissions.

Six simulations, differentiating mostly in Chinese anthropogenic emissions, are conducted from December 2005 through 2006, using initial conditions provided from previous spin-up simulations starting from January 2004. Emissions are perturbed for SO_2, NO_x, CO, BC and OC; emissions of VOC are generally kept unchanged unless stated otherwise. The base simulation (Simulation 1) is driven by total emissions in China from anthropogenic sources derived in this study. The following two simulations subtract total Chinese emissions by EEE (Simulation 2) and EEE related to production of goods for consumption in the U.S. (about 21% of the total EEE; Simulation 3), respectively, to quantify the impacts of trade-induced emissions on regional air quality and global transport.

Simulation 4 subtracts the total Chinese emissions by the amount of reduced EEE if the U.S. industrial and emission control technologies were applied to China (see Sect. 7 for discussion of their differences). Comparing Simulation 4 and Simulation 3 shows the impact of improved technologies on Chinese EEE and the consequent global transport.

Simulation 5 incorporates assumed EEE of VOC at 20% of Chinese total for comparison with Simulation 2; it better simulates the impact of EEE on the ozone formation. Specifically, Eq. 15 is used to calculate EEE of VOC. In deriving emission intensity for each sector, however, emissions in 2010 allocated to eight sectors by Klimont et al.(50) are re-distributed to the 42 sectors here. Differences in emission factors are neglected between sectors here that are mapped to the same sector in Klimont et al., due to lack of detailed information. As a result, the EEE of NO_x, VOC and CO together enhance the annual mean surface ozone concentrations by 0-2% over the North China Plain (Fig. S6). Meanwhile, ozone concentrations outside of China are enhanced by the Chinese EEE of NO_x and CO, whether or not the EEE of VOC are considered in the simulations (comparing Fig. 2b and Fig. S6).

Simulation 6 is conducted for comparison with Simulation 3. In addition to the perturbation of Chinese emissions as in Simulation 3, it assumes an increase of pollutant emissions in the U.S. if goods imported from China were produced in the U.S. instead.

7. Understanding the high emission/GDP ratio of China relative to the U.S. level and impacts of less advanced technology level

Per unit of GDP in 2006, China emits 4.9 times as much CO_2 and 6.0 – 32.5 times as much air pollution as the U.S. (Table S1). The relatively high emission/GDP ratio of China is caused in part by its manufacture-dominant economic structure. In 2006, its manufacturing industry contributes 43% of GDP (11), compared to 12% for the U.S. (http://www.bea.gov/industry/iedguide.htm#gdpia_ou). Chinese economy also relies mostly on coal as energy source with relatively low energy efficiency. In addition, emission factors for air pollutants are relatively high in China with less advanced emission control technologies. China emits 8.12 grams of SO_2, 4.05 grams of NO_x and 1.65 grams of CO for a kilowatt hour (kWh) of coal-fired electricity generation in 2005, about 1.6-7.0 times as large as the U.S. level (Table S11). By comparison, emission factors of CO_2 differ only by 7% between China and the U.S. (Table S11) due to lack of decarbonizing processes in both countries.

Differences in the emission/GDP ratio between China and the U.S. (Table S1) are attributed to economic structure, energy efficiency and emission control technology. To quantify the combined effect of energy efficiency and emission control technology, differences in the emission/GDP ratio for CO_2 between the two countries are assumed to be caused solely by differences in their economic structures (i.e., differences in energy efficiency and emission factor are negligible for CO_2 for any given combustion or non-combustion process, as demonstrated above for the coal-fired power industry). As such the combined effect of energy efficiency and emission control technology can be derived by dividing the ratio between China and the U.S. for emissions per GDP of a given short-lived air pollutant by the ratio for CO_2. While the estimate here is relatively rough, it does provide some insight into the differences in energy efficiency and emission controls between the two countries.

Table S1. Emission/GDP of China divided by that of trade partners in 2006 [a]

Pollutants	China/US	China/EU	China/Japan [b]	China/Others	China/world
CO_2	4.9	7.0	10.2	2.5	3.3
SO_2	12.4	17.7	75.3	3.5	4.9
NO_x	6.0	8.1	24.4	2.7	3.6
CO	9.9	23.0	161.0	3.0	4.5
BC	22.5	15.8	58.5	3.8	5.3
OC	32.5	22.2	179.8	3.6	5.2

[a] The quantity of 'emission/GDP' is closely related to the overall emission intensity defined as emissions per unit of total monetary outputs. Data sources: World Bank for GDP and population (http://data.worldbank.org/); this study for emissions of all pollutants in China; Bond et al. (15) for BC and OC emissions in other countries; NEI05 for SO_2, NO_x and CO emissions in the U.S. (http://www.epa.gov/ttnchie1/trends/); EMEP for SO_2, NO_x and CO emissions in the EU (http://www.ceip.at/webdab-emission-database/); and REAS (14) for SO_2, NO_x and CO emissions in Japan.

Table S2. Projection of 45 sectors in energy data to the 42 IOT sectors

No.	Sector in energy data	Sector in IOTs
1	Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy	Agriculture
2	Coal Mining and Dressing	Coal Mining and Processing
3	Petroleum and Natrual Gas Extraction	Petroleum and Natural Gas Extraction
4	Ferrous Metals Mining and Dressing	Metals Mining and Dressing
5	Nonferrous Metals Mining and Dressing	Metals Mining and Dressing
6	Nonmental Minerals Mining and Dressing	Nonmetal Minerals Mining and Dressing
7	Other Minerals Mining and Dressing	Nonmetal Minerals Mining and Dressing
8	Logging and Transport of Wood and Bamboo	Agriculture
9	Food Processing	Food Production and Tobacco Processing
10	Food Production	Food Production and Tobacco Processing
11	Beverage Production	Food Production and Tobacco Processing
12	Tobacco Processing	Food Production and Tobacco Processing
13	Textile Industry	Textile Industry
14	Garments and Other Fibers Products	Garments, Leather, Down and Other Fiber Products Manufacturing
15	Leather, Furs, Down and Related Products	Garments, Leather, Down and Other Fiber Products Manufacturing
16	Timber Processing, Bamboo, Cane, Palm Fiber & Straw Products	Timber Processing and Furniture Manufacturing
17	Furniture manufacturing	Timber Processing and Furniture Manufacturing
18	Papermaking and Paper Products	Papermaking, Printing, Cultural and Educational Goods Manufacturing
19	Printing and Record Medium Reproduction	Papermaking, Printing, Cultural and Educational Goods Manufacturing
20	Cultural, Educational and Sports Articles	Papermaking, Printing, Cultural and Educational Goods Manufacturing
21	Petroleum Processing and Coking	Petroleum Refining and Coking
22	Raw Chemical Materials and Chemical Products	Chemical Industry
23	Medical and Pharmaceutical Products	Chemical Industry
24	Chemical Fiber	Chemical Industry
25	Rubber Products	Chemical Industry
26	Plastic Products	Chemical Industry
27	Nonmetal Mineral Products	Nonmetal Mineral Products
28	Smelting and Pressing of Ferrous Metals	Smelting and Pressing of Metals
29	Smelting and Pressing of Nonferrous Metals	Smelting and Pressing of Metals
30	Metal Products	Metal Products

31	Ordinary Machinery	Machinery Industry
32	Equipment for Special Purposes	Machinery Industry
33	Transportation Equipment	Transport Equipment Manufacturing
34	Electric Equipment and Machinery	Electric Equipment and Machinery Manufacturing
35	Electronic and Telecommunications Equipment	Electronic and Telecommunications Equipment Manufacturing
36	Instruments, Meters, Cultural and Office Machinery	Instruments, Meters, Cultural and Clerical Machinery Manufacturing
37	Other Manufacturing Industry	Other Manufacturing
38	Production and Supply of Electric Power, Steam and Hot Water	Production and Supply of Electric Power, Steam and Hot Water
39	Production and Supply of Gas	Production and Supply of Gas
40	Production and Supply of Tap Water	Production and Supply of Tap Water
41	Construction	Construction
42	Transportation, Storage, Postal & Telecommunications Sevices	Traffic,transport, storage
43	Wholesale, Retail Trade and Catering Services	Wholesale and retail trade
44	Others	N/A
45	Residential Consumption	N/A

Table S3. Emission factors for main non-combustion industrial processes

Pollutant	Process	Technology	Unit	Value
SO_2 [a]	cement production	precalciner kiln	kg/t-coal	2.9
	cement production	other rotary kiln	kg/t-coal	12.3
	cement production	shaft kiln	kg/t-coal	12.3
CO [b]	coking	machinery	kg/t-coke	1.6
	coking	indigenous	kg/t-coke	15.6
	sinter production	sintering	kg/t-sinter	22
	iron production	blast furnace	kg/t-iron	40.5
	steel making	basic oxygen furnace	kg/t-steel	54.2
	steel making	electric arc furnace	kg/t-steel	9
	synthetic ammonia	coal-based	kg/t-NH_3	43
	cement production	precalciner kiln	kg/t-coal	17.8
	cement production	other rotary kiln	kg/t-coal	17.8
	cement production	shaft kiln	kg/t-coal	155.7
	brick production	tunnel kiln	kg/t-coal	150
	lime production	shaft kiln, beehive kiln	kg/t-coal	155.7
NO_x [c]	cement production	precalciner kiln	kg/t-coal	15.3
	cement production	other rotary kiln	kg/t-coal	18.5
	cement production	shaft kiln	kg/t-coal	1.7
	brick production	tunnel kiln	kg/t-coal	4.7
	lime production	shaft kiln, beehive kiln	kg/t-coal	1.7

[a] Collected from Lei et al. (18).
[b] Collected from Streets et al. (30).
[c] Collected from Lei et al. (21) and Zhang et al. (25).

Table S4. Mapping between the 42 sectors in IOTs of 2002-2009 and the 17 sectors in IOTs of 2000-2001

No.	Sector in 42-sector IOTs	Sector in 17-sector IOTs
1	Agriculture	Agriculture
2	Coal Mining and Processing	Mining and Quarrying
3	Petroleum and Natural Gas Extraction	Coking, Gas and Petroleum Refining
4	Metals Mining and Dressing	Mining and Quarrying
5	Nonmetal Minerals Mining and Dressing	Mining and Quarrying
6	Food Production and Tobacco Processing	Foodstuff
7	Textile Industry	Textile, Sewing, Leather and Furs Products
8	Garments, Leather, Down and Other Fiber Products Manufacturing	Textile, Sewing, Leather and Furs Products
9	Timber Processing and Furniture Manufacturing	Other Manufacturing
10	Papermaking, Printing, Cultural and Educational Goods Manufacturing	Other Manufacturing
11	Petroleum Refining and Coking	Coking, Gas and Petroleum Refining
12	Chemical Industry	Chemical Industry
13	Nonmetal Mineral Products	Building Materials and Non-metal Mineral Products
14	Smelting and Pressing of Metals	Metal Products
15	Metal Products	Metal Products
16	Machinery Industry	Machinery and Equipment
17	Transport Equipment Manufacturing	Machinery and Equipment
18	Electric Equipment and Machinery Manufacturing	Machinery and Equipment
19	Electronic and Telecommunications Equipment Manufacturing	Machinery and Equipment
20	Instruments, Meters, Cultural and Clerical Machinery Manufacturing	Machinery and Equipment
21	Other Manufacturing	Other Manufacturing
22	Waster and Flotsam	Other Services
23	Production and Supply of Electric Power, Steam and Hot Water	Production and Supply of Electric Power, Heat Power and Water
24	Production and Supply of Gas	Coking, Gas and Petroleum Refining
25	Production and Supply of Tap Water	Production and Supply of Electric Power, Heat Power and Water
26	Construction	Construction
27	Traffic, transport, storage	Transportation, Postal and Telecommunication Services

28	Post	Transportation, Postal and Telecommunication Services
29	Information transfer, computer services and software	Transportation, Postal and Telecommunication Services
30	Wholesale and retail trade	Wholesale and Retail Trades, Hotels and Catering Services
31	Accommodation and Restaurants	Wholesale and Retail Trades, Hotels and Catering Services
32	Banking and Insurance	Banking and Insurance
33	Real Estate Trade	Real Estate, Leasing and Business Services
34	Tenancy and business services	Real Estate, Leasing and Business Services
35	Tourism	Other Services
36	Scientific research	Other Services
37	Compositive technical service	Other Services
38	Other social work	Other Services
39	Education	Other Services
40	Sanitation, social security and social welfare	Other Services
41	Culture, sports and entertainment	Other Services
42	Public management and social organization	Other Services

Table S5. Data sources for activity rates and technology distribution

Sector	Data source for activity data	Data source for technology distribution
Power plants	China Energy Statistical Yearbook (24)	Zhang et al. (10) Zhao et al. (33)
Industry boilers	China Energy Statistical Yearbook (24)	China Industrial Economy Statistical Yearbook (51) Unpublished data from China Electrical Equipment Industrial Association
Residential combustion	China Energy Statistical Yearbook (24)	N/A
Coke production	China Energy Statistical Yearbook (24)	National Bureau of Statistics (11)
Cement production	China Cement Almanac (28)	China Cement Almanac (24)
Iron & Steel production	China Iron and Steel Statistics (27)	China Iron and Steel Statistics (27)
Vehicles [a]	China Vehicle Emission Control Annual Report (29) Year Book of China Transportation and Communications (32)	He et al. (2005) (31)

[a] Oil usage in the transportation sector are calculated by Eq. 21. Vehicle population (VP) is obtained from the China Vehicle Emission Control Annual Report (29). Annual average vehicle mileage traveled (VM) is derived from the Year Book of China Transportation and Communications (32) based on the approach by He et al. (31)

Table S6. Emission factors for different fuels used in various sectors

Sector	Fuel type	Net emission factor (after implementing control measures; kg/GJ)				
		SO_2 [a]	CO [b]	NO_x [c]	BC [d]	OC [d]
Power	Coal	0.20~0.92	0.047~0.052	0.142~0.165	0.0006~0.0012	0.0003~0.0012
	Oil	0.20	0.026	0.375	0.0006~0.0008	0.0003~0.0004
	Natural gas	0	0.0051	0.0160	0	0
Industry	Coal	0.44~0.61	0.33~0.49	0.09~0.11	0.010~0.029	0.009~0.030
	Oil	0.19~0.21	0.026	0.307	0.025~0.035	0.008~0.011
	Natural gas	0	0.0051	0.0081	0	0
Residential	Coal	0.66~0.75	1.05~1.36	0.07~0.08	0.053~0.081	0.12~0.15
	Oil	0.14	0.026	0.196	0.058~0.070	0.019~0.022
	Biofuel	0.012	2.99	0.08	0.058	0.21
	Natural gas	0	0.0051	0.0057	0	0
Transportation	On-road gasoline	0.005~0.13	8.61~28.24	0.78~1.29	0.064~0.079	0.019~0.024
	On-road diesel	0.002~0.23	1.71~5.33	2.13~2.86	0.011~0.014	0.043~0.073
	Off-road oil	0.20~0.25	5.03	1.96	0.030~0.045	0.015~0.020

[a] Derived from Lu et al. (18).
[b] Derived from Streets et al. (30) and Zhang et al. (10).
[c] Derived from Zhang et al. (10, 25).
[d] Derived from Lu et al. 2011 (18).

Table S7. Mapping between the trade coding chapters and the 42 IOT sectors

No.	Trade coding chapter	Sector in IOTs
1	Live animals	Agriculture
2	Meat and edible offal	Agriculture
3	Fish and crustaceans, molluscs, and other aquatic invertebrates	Agriculture
4	Dairy produce; birds' eggs; natural honey; edible products of animal origin, not elsewhere specified or included	Agriculture
5	Products of animal origin, not elsewhere specified or included	Agriculture
6	Live trees and other plants; bulbs, roots, and the like; cut flowers and ornamental foliage	Agriculture
7	Edible vegetables and certain roots and tubers	Agriculture
8	Edible fruit and nuts; peel of citrus fruit or melons	Agriculture
9	Coffee, tea, maté, and spices	Agriculture
10	Cereals	Agriculture
11	Products of the milling industry; malt; starches; inulin; wheat gluten	Agriculture
12	Oil seeds and oleaginous fruits; miscellaneous grains, seeds, and fruit; industrial or medicinal plants; straw and fodder	Agriculture
13	Lac; gums, resins, and other vegetable saps and extracts	Agriculture
14	Vegetable plaiting materials; vegetable products not elsewhere specified or included	Agriculture
15	Animal or vegetable fats and oils and their cleavage products; prepared edible fats; animal or vegetable waxes	Food Production and Tobacco Processing
16	Preparations of meat, of fish or of crustaceans, molluscs, or other aquatic invertebrates	Food Production and Tobacco Processing
17	Sugars and sugar confectionery	Food Production and Tobacco Processing
18	Cocoa and cocoa preparations	Food Production and Tobacco Processing
19	Preparations of cereals, flour, starch, or milk; pastrycooks' products	Food Production and Tobacco Processing
20	Preparations of vegetables, fruit, nuts, or other parts of plants	Food Production and Tobacco Processing
21	Miscellaneous edible preparations	Food Production and Tobacco

		Processing
22	Beverages, spirits, and vinegar	Food Production and Tobacco Processing
23	Residues and waste from the food industries; prepared animal fodder	Food Production and Tobacco Processing
24	Tobacco and manufactured tobacco substitutes	Food Production and Tobacco Processing
25	Salt; sulphur; earth and stone; plastering materials, lime, and cement	Nonmetal Mineral Products
26	Ores, slag, and ash	Nonmetal Minerals Mining and Dressing
27	Mineral fuels, mineral oils, and products of their distillation; bituminous substances; mineral waxes	Petroleum and Natural Gas Extraction
28	Inorganic chemicals; organic or inorganic compounds of precious metals, of rare-earth metals, of radioactive elements or of isotopes	Chemical Industry
29	Organic chemicals	Chemical Industry
30	Pharmaceutical products	Chemical Industry
31	Fertilisers	Chemical Industry
32	Tanning or dyeing extracts; tannins and their derivatives; dyes, pigments, and other colouring matter; paints and varnishes; putty and other mastics; inks	Chemical Industry
33	Essential oils and resinoids; perfumery, cosmetic, or toilet preparations	Chemical Industry
34	Soap, organic surface-active agents, washing preparations, lubricating preparations, artificial waxes, prepared waxes, polishing or scouring preparations, candles and similar articles, modelling pastes, "dental waxes" and dental preparations with a basis of plaster	Chemical Industry
35	Albuminoidal substances; modified starches; glues; enzymes	Chemical Industry
36	Explosives; pyrotechnic products; matches; pyrophoric alloys; certain combustible preparations	Chemical Industry
37	Photographic or cinematographic goods	Chemical Industry
38	Miscellaneous chemical products	Chemical Industry
39	Plastics and articles thereof	Chemical Industry
40	Rubber and articles thereof	Chemical Industry
41	Raw hides and skins	Garments, Leather, Down and Other Fiber Products Manufacturing

42	Articles of leather; saddlery and harness; travel goods, handbags, and similar containers; articles of animal gut	Garments, Leather, Down and Other Fiber Products Manufacturing
43	Furskins and artificial fur; manufactures thereof	Garments, Leather, Down and Other Fiber Products Manufacturing
44	Wood and articles of wood; wood charcoal	Timber Processing and Furniture Manufacturing
45	Cork and articles of cork	Timber Processing and Furniture Manufacturing
46	Manufactures of straw, of esparto, or of other plaiting materials; basketware and wickerwork	Timber Processing and Furniture Manufacturing
47	Pulp of wood or of other fibrous cellulosic material; recovered	Papermaking, Printing, Cultural and Educational Goods Manufacturing
48	Paper and paperboard; articles of paper pulp, of paper or of paperboard	Papermaking, Printing, Cultural and Educational Goods Manufacturing
49	Printed books, newspapers, pictures, and other products of the printing industry; manuscripts, typescripts and plans	Papermaking, Printing, Cultural and Educational Goods Manufacturing
50	Silk	Textile Industry
51	Wool, fine or coarse animal hair; horsehair yarn, and woven fabric	Textile Industry
52	Cotton	Textile Industry
53	Other vegetable textile fibres; paper yarn, and woven fabrics of paper yarn	Textile Industry
54	Man-made filaments; strip and the like of man-made textile materials	Textile Industry
55	Man-made staple fibres	Textile Industry
56	Wadding, felt, and nonwovens; special yarns; twine, cordage, ropes and cables and articles thereof	Textile Industry
57	Carpets and other textile floor coverings	Textile Industry
58	Special woven fabrics; tufted textile fabrics; lace; tapestries; trimmings; embroidery	Textile Industry
59	Impregnated, coated, covered, or laminated textile fabrics; textile articles of a kind suitable for industrial use	Textile Industry
60	Knitted or crocheted fabrics	Textile Industry
61	Articles of apparel and clothing accessories, knitted or crocheted	Textile Industry
62	Articles of apparel and clothing accessories, not knitted or crocheted	Textile Industry

63	Other made up textile articles; sets; worn clothing and worn textile articles; rags	Textile Industry
64	Footwear, gaiters and the like; parts of such articles	Garments, Leather, Down and Other Fiber Products Manufacturing
65	Headgear and parts thereof	Garments, Leather, Down and Other Fiber Products Manufacturing
66	Umbrellas, sun umbrellas, walking-sticks, seat-sticks, whips, riding-crops, and parts thereof	Garments, Leather, Down and Other Fiber Products Manufacturing
67	Prepared feathers and down and articles made of feathers or of down; artificial flowers; articles of human hair	Garments, Leather, Down and Other Fiber Products Manufacturing
68	Articles of stone, plaster, cement, asbestos, mica, or similar materials	Nonmetal Mineral Products
69	Ceramic products	Nonmetal Mineral Products
70	Glass and glassware	Nonmetal Mineral Products
71	Natural or cultured pearls, precious or semi-precious stones, precious metals, metals clad with precious metal and articles thereof; imitation jewellery; coin	Metal Products
72	Iron and steel	Smelting and Pressing of Metals
73	Articles of iron or steel	Metal Products
74	Copper and articles thereof	Metal Products
75	Nickel and articles thereof	Metal Products
76	Aluminium and articles thereof	Metal Products
77	Reserved for possible future use in the Harmonised System	Metal Products
78	Lead and articles thereof	Metal Products
79	Zinc and articles thereof	Metal Products
80	Tin and articles thereof	Metal Products
81	Other base metals; cermets; articles thereof	Metal Products
82	Tools, implements, cutlery, spoons, and forks of base metal; parts thereof of base metal	Metal Products
83	Miscellaneous articles of base metal	Metal Products
84	Nuclear reactors, boilers, machinery and mechanical appliances; parts thereof	Machinery Industry
85	Electrical machinery and equipment and parts thereof; sound recorders and reproducers, television image and sound recorders and reproducers, and parts and accessories of such articles	Electric Equipment and Machinery Manufacturing

86	Railway or tramway locomotives, rolling-stock and parts thereof; railway or tramway track fixtures and fittings and parts thereof; mechanical	Transport Equipment Manufacturing
87	Vehicles other than railway or tramway rolling-stock, and parts and accessories thereof	Transport Equipment Manufacturing
88	Aircraft, spacecraft, and parts thereof	Transport Equipment Manufacturing
89	Ships, boats, and floating structures	Transport Equipment Manufacturing
90	Optical, photographic, cinematographic, measuring, checking, precision, medical or surgical instruments and apparatus; parts and accessories thereof	Instruments, Meters, Cultural and Clerical Machinery Manufacturing
91	Clocks and watches and parts thereof	Instruments, Meters, Cultural and Clerical Machinery Manufacturing
92	Musical instruments; parts and accessories of such articles	Instruments, Meters, Cultural and Clerical Machinery Manufacturing
93	Arms and ammunition; parts and accessories thereof	Instruments, Meters, Cultural and Clerical Machinery Manufacturing
94	Furniture; bedding, mattresses, mattress supports, cushions, and similar stuffed furnishings; lamps and lighting fittings, not elsewhere specified or included; illuminated signs, illuminated name-plates and the like; prefabricated buildings	Timber Processing and Furniture Manufacturing
95	Toys, games, and sports requisites; parts and accessories thereof	Other Manufacturing
96	Miscellaneous manufactured articles	Other Manufacturing
97	Works of art, collectors' pieces, and antiques	N/A
98	Commodities and transactions not classified according to kind	N/A

Table S8. Emission intensity for CO_2, SO_2 and NO_x in 2002, 2005 and 2007 [a]

Sector	Emission intensity								
	CO_2 (kg/RMB)			SO_2 (g/RMB)			NO_x (g/RMB)		
	2002	2005	2007	2002	2005	2007	2002	2005	2007
Production and Supply of Electric Power, Steam and Hot Water	1.09	1.00	0.89	11.9	8.02	5.24	5.16	4.46	3.70
Building Materials and Non-metal Mineral Products	0.48	0.42	0.40	1.49	1.07	0.94	0.78	1.16	1.30
Metal Products	0.20	0.23	0.16	1.10	1.16	0.78	0.30	0.34	0.24
Mining and Quarrying	0.16	0.16	0.15	0.87	0.80	0.69	0.26	0.17	0.12
Coking, Gas and Petroleum Refining	0.14	0.13	0.11	0.6	0.5	0.4	0.16	0.15	0.13
Transportation, Post and Telecommunications	0.097	0.094	0.092	0.18	0.14	0.086	2.6	2.0	1.7
Chemical Industry	0.086	0.078	0.070	0.46	0.38	0.33	0.14	0.13	0.11
Agriculture	0.036	0.040	0.034	0.13	0.14	0.12	0.022	0.024	0.021
Other Manufacturing	0.033	0.043	0.038	0.17	0.21	0.18	0.0091	0.0096	0.0078
Foodstuff	0.033	0.023	0.020	0.17	0.11	0.092	0.012	0.0079	0.0059
Textile, Sewing, Leather and Furs Products	0.018	0.019	0.018	0.090	0.091	0.080	0.0084	0.0055	0.0044
Machinery and Equipment	0.011	0.0085	0.0069	0.051	0.038	0.030	0.012	0.0096	0.0077
Construction	0.0086	0.0099	0.0074	0.034	0.036	0.026	0.014	0.016	0.011

[a] Data are presented for the 13 main sectors out of the 17 (corresponding to the IOT of 2000) sectors grouped from the 42 sectors used in our IOA. See Table S4 for sector mapping.

Table S9. Emission intensity for CO, OC and BC in 2002, 2005 and 2007 [a]

Sector	Emission intensity CO (g/RMB)			OC (g/RMB)			BC (g/RMB)		
	2002	2005	2007	2002	2005	2007	2002	2005	2007
Production and Supply of Electric Power, Steam and Hot Water	2.21	1.63	1.46	0.012	0.0073	0.0060	0.0094	0.0049	0.0033
Building Materials and Non-metal Mineral Products	37.1	18.0	13.7	0.069	0.042	0.034	0.062	0.039	0.030
Metal Products	6.8	7.4	5.3	0.046	0.043	0.026	0.046	0.041	0.025
Mining and Quarrying	0.38	0.39	0.36	0.041	0.033	0.026	0.036	0.029	0.023
Coking, Gas and Petroleum Refining	0.72	0.73	0.47	0.032	0.025	0.020	0.031	0.024	0.018
Transportation, Post and Telecommunications	16	12	10	0.079	0.074	0.069	0.068	0.062	0.062
Chemical Industry	2.07	1.89	1.65	0.020	0.015	0.012	0.019	0.014	0.011
Agriculture	0.029	0.035	0.024	0.014	0.015	0.0094	0.0059	0.0061	0.0036
Other Manufacturing	0.62	0.86	0.77	0.0081	0.0085	0.0066	0.0072	0.0075	0.0057
Foodstuff	0.69	0.50	0.44	0.0081	0.0049	0.0037	0.0071	0.0040	0.0030
Textile, Sewing, Leather and Furs Products	0.038	0.044	0.041	0.0046	0.0040	0.0033	0.0038	0.0033	0.0026
Machinery and Equipment	0.016	0.013	0.010	0.0030	0.0021	0.0016	0.0022	0.0014	0.001
Construction	0.0092	0.0090	0.0065	0.0031	0.0036	0.0030	0.0015	0.0015	0.0011

[a] Data are presented for the 13 main sectors out of the 17 (corresponding to the IOT of 2000) sectors grouped from the 42 sectors used in our IOA. See Table S4 for sector mapping.

Table S10. Uncertainties in trade-induced emissions of China averaged over 2000 to 2009

	CO_2	SO_2	NO_x	CO	BC	OC
EEE	[-15,15]	[-17,17]	[-27,27]	[-45,45]	[-35,51]	[-41,60]
EAI	[-15,15]	[-16,16]	[-25,25]	[-41,41]	[-33,46]	[-38,55]
EEI	[-21,21]	[-52,52]	[-56,56]	[-65,65]	[-60,68]	[-63,74]

Table S11. Emission factors for coal-fired power generation in China and the U.S.

Pollutant	China (g/kWh) a	U.S. (g/kWh) b
CO_2	1075	1004
SO_2	8.12	5.09
NO_x	4.05	1.72
CO	1.65	0.24

[a] Data are derived from this study.
[b] Values are calculated based on the NEI05 emission inventory (http://www.epa.gov/ttn/chief/net/2005inventory.html#inventorydata) and electricity data from the Energy Information Administration (http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0802c).

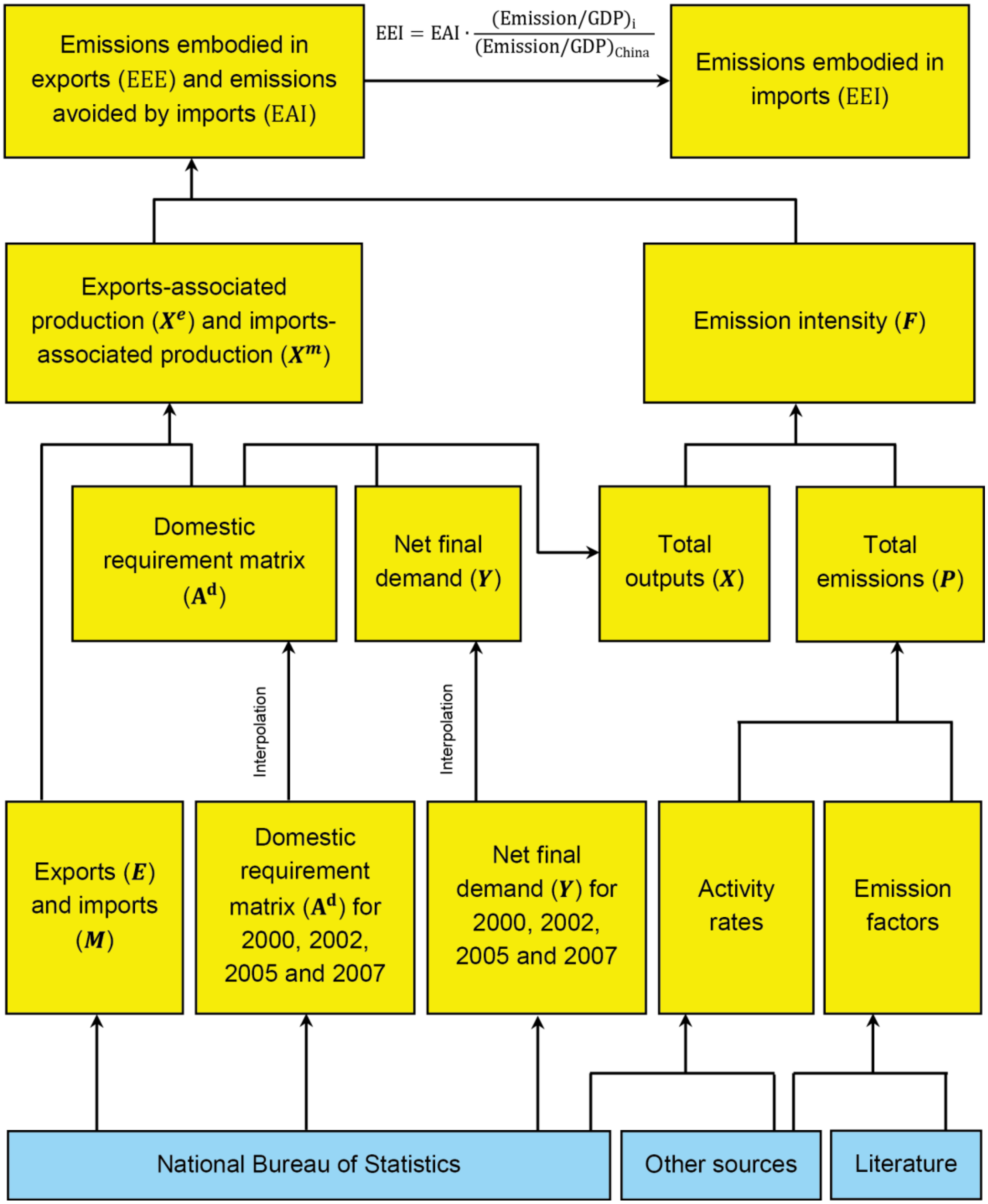

Figure S1. Schematic methodology for estimating trade-induced emissions of China. Unless otherwise specified, data are available over 2000 – 2009. See section 2.1 (Input-output tables) of Material and Methods for interpolation of domestic requirement matrix and section 2.4 (Economic data) for interpolation of net final demand.

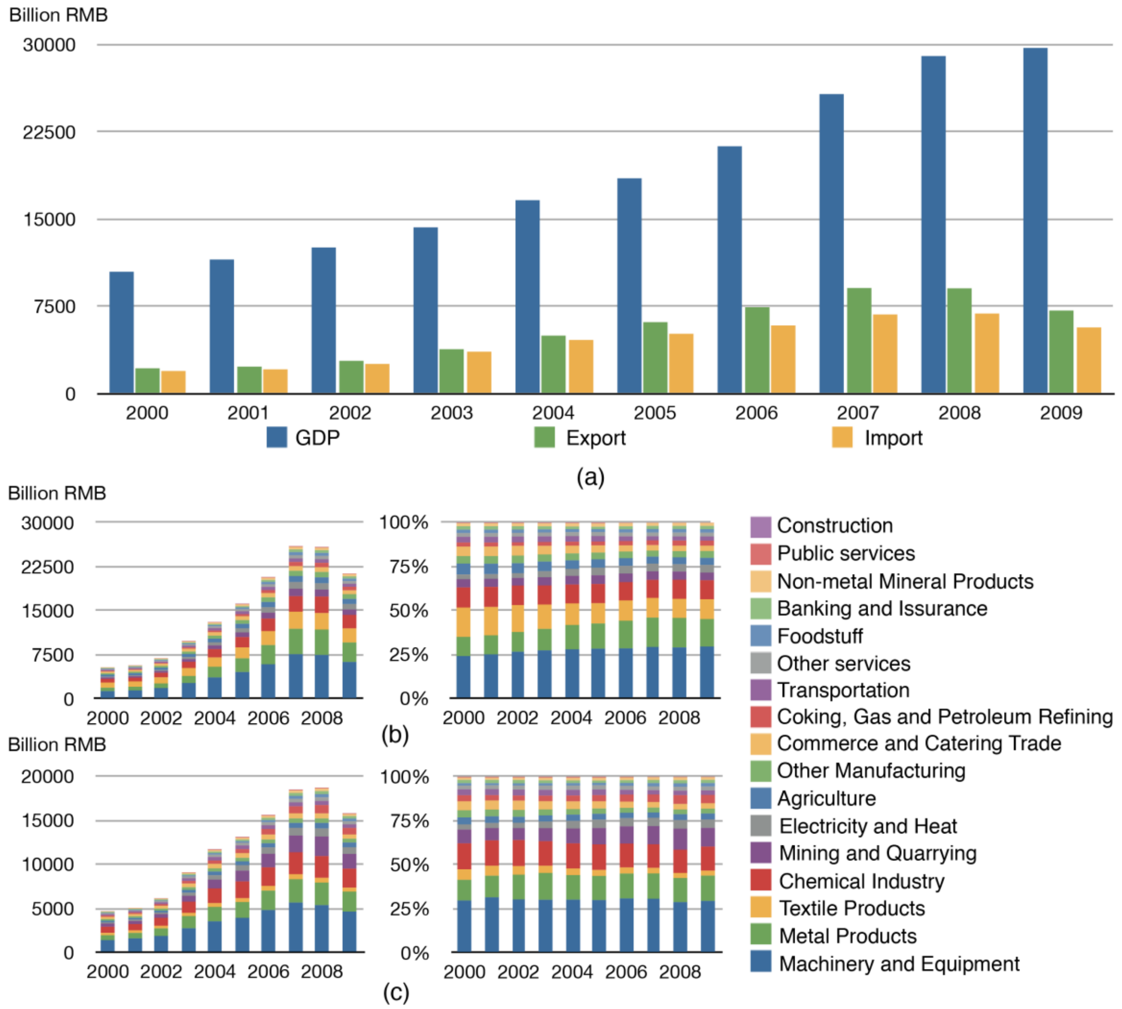

Figure S2. GDP, imports and exports of China over 2000 – 2009. Values are adjusted to 2005 prices based on PPI. (a) GDP, imports and exports. (b) Exported production ($\boldsymbol{X}^e$) from 17 sectors and sectoral contributions (in percentage). (c) Imported production ($\boldsymbol{X}^m$) from 17 sectors and sectoral contributions (in percentage). The 17 sectors correspond to the IOT of 2000.

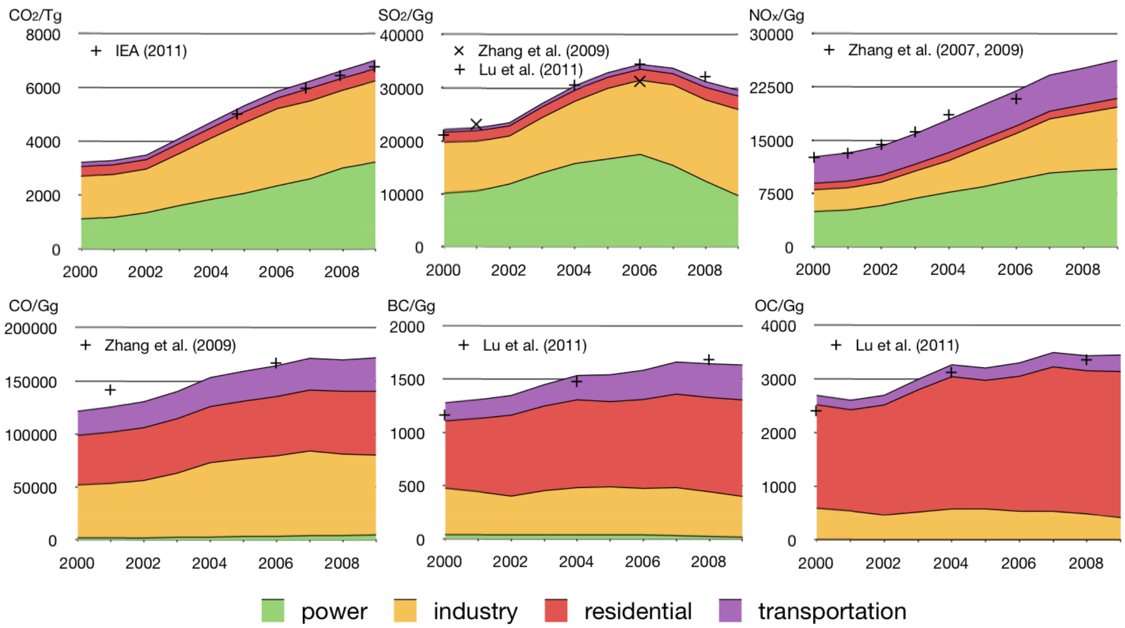

Figure S3. Total anthropogenic emissions of CO_2 and air pollutants in China from four major sectors over 2000-2009. Previous studies are shown also for comparison. The reduction of SO_2 emissions from the power sector since 2006 was due mainly to the enforced FGD system.

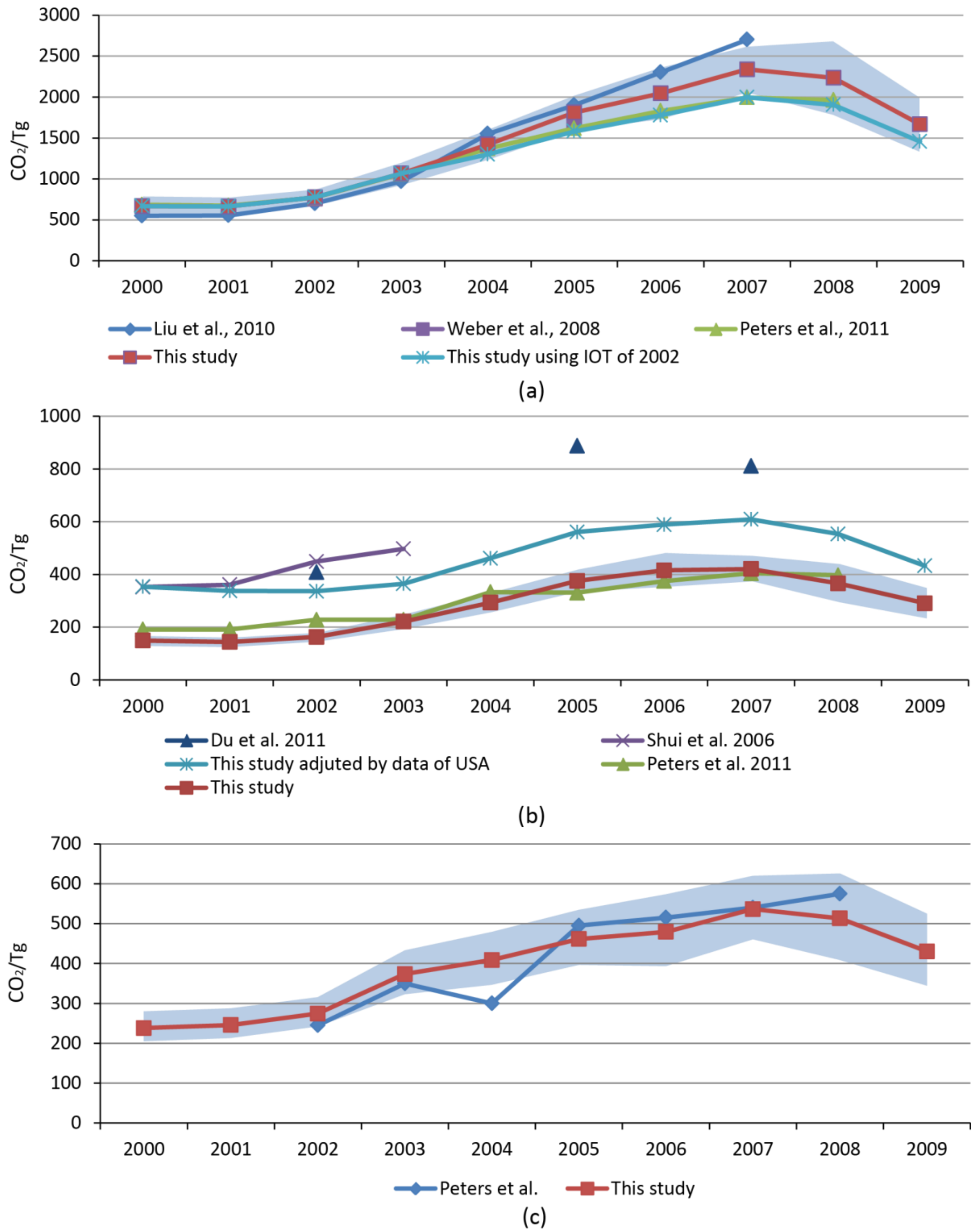

Figure S4. Trade-related anthropogenic emissions of CO_2 in China in comparison with previous studies. (a) EEE. (b) EEE due to exporting goods to the U.S. alone. (c) EEI. Shaded areas represent the 95% confidence interval derived with the Monte Carlo simulation in this study.

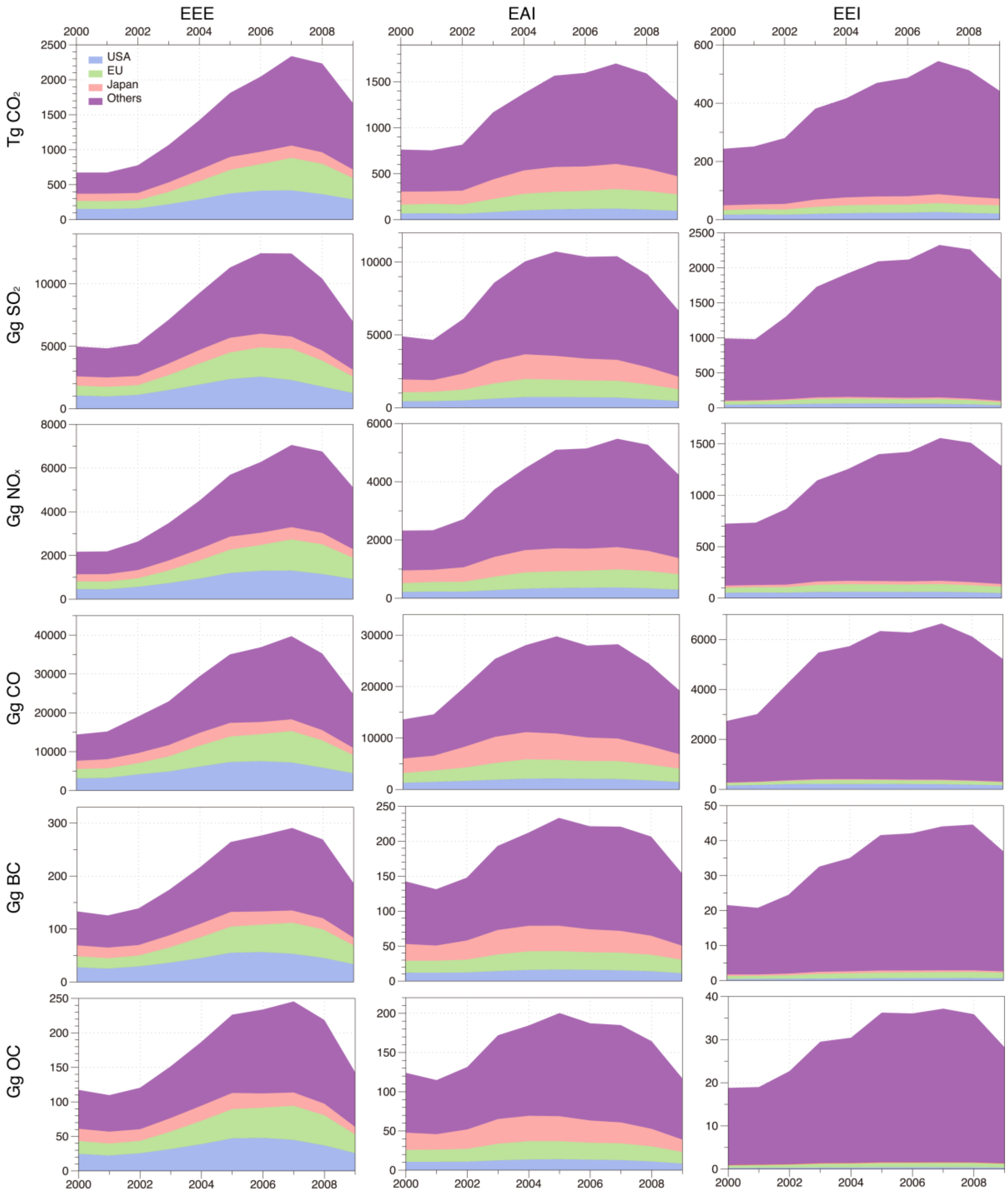

Figure S5. EEE, EAI and EEI of China over 2000 – 2009 with respect to different trade partners.

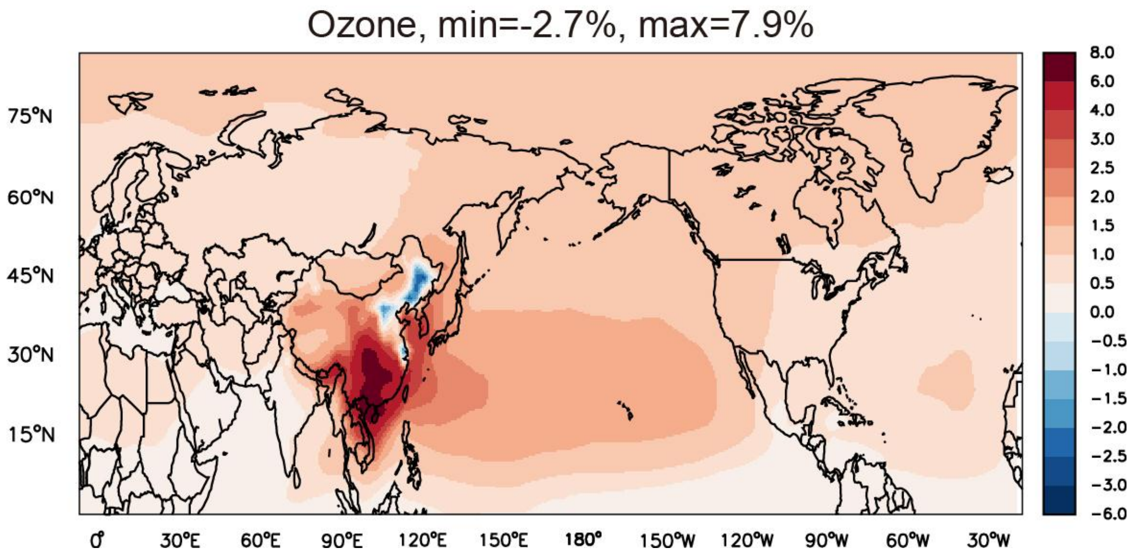

Figure S6. Simulated percentage contribution of surface ozone in 2006 from Chinese EEE of NO_x, CO and VOC. Results are shown for annual mean concentrations in the lowest model layer (0-130 m), presented as (Simulation 1 – Simulation 5) / Simulation 1 in Sect. 6. The color scale is nonlinear to better present the wide range of impacts over different regions. Compared to results shown in Fig. 2b, the EEE of VOC are accounted for here, leading to enhanced ozone production efficiency of NO_x. The effect is most evident over the North China Plain.

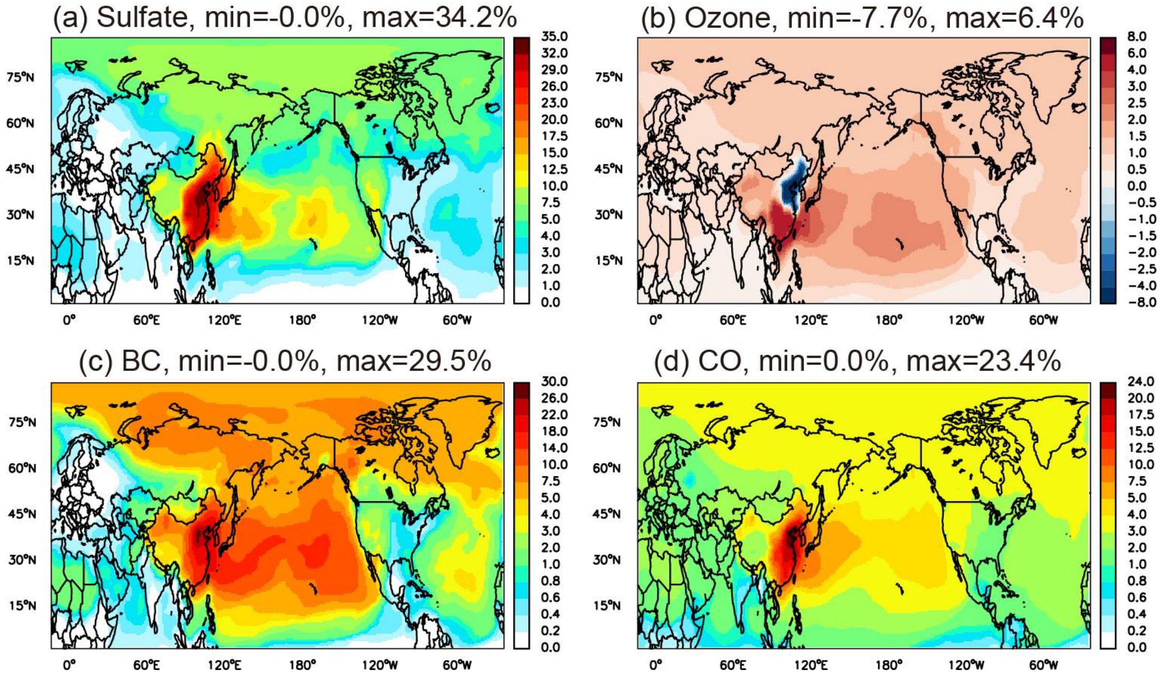

Figure S7. Simulated percentage contribution of surface air pollution in April 2006 from Chinese EEE. Results are shown for monthly mean concentrations in the lowest model layer (0-130 m), presented as (Simulation 1 – Simulation 2) / Simulation 1 in Sect. 6. The color scale is nonlinear to better present the wide range of impacts over different regions. Compared to their annual-mean contribution shown in Fig. 2, the contribution of EEE-related Chinese pollution to the downwind regions is enhanced in spring due to greater eastward cyclonic activities.

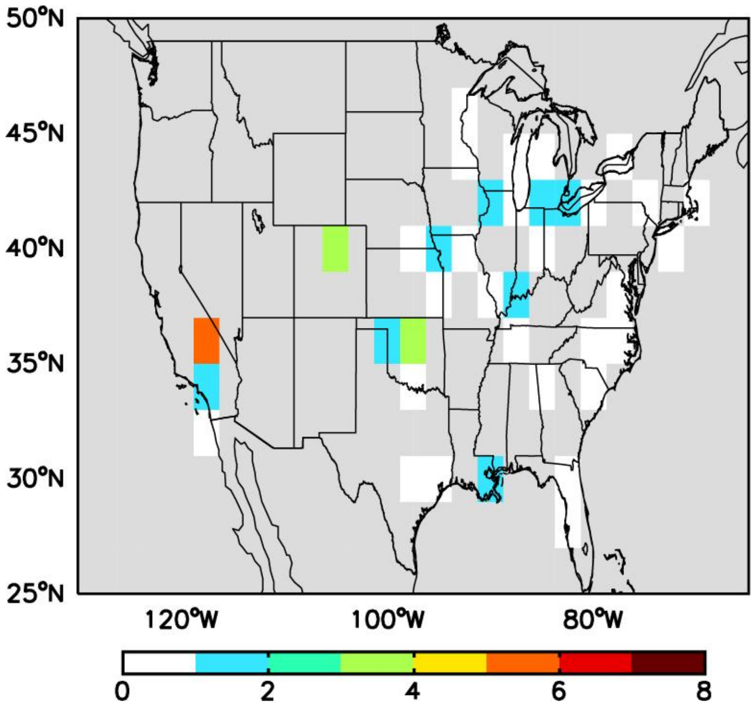

Figure S8. Simulated number of days in 2006 when daily maximum eight-hour average ozone concentration would not have exceeded the current U.S. standard (75 ppb) but not for the transport of the EEE-related Chinese air pollution. There are 38 model gridcells (out of the 217 gridcells constituting the contiguous U.S.) that have such an exceedance situation, including the gridcells covering the Los Angeles area and many regions in the eastern U.S. The white color represents one extra day of exceedance. The areas colored in gray do not have such an exceedance situation.

References

1. Leontief W (1986) *Input-output economics* (Oxford University Press, USA).
2. Miller RE & Blair PD (1985) *Input-Output Analysis: Foundations and Extensions* (Prentice-Hall, Englewood Cliffs, NJ).
3. HIOTCA (1999) *Handbook of input-output table compilation and analysis* (United Nations).
4. Lin B & Sun C (2010) Evaluating carbon dioxide emissions in international trade of China. *Energy Policy* 38(1):613-621.
5. Liu X, Ishikawa M, Wang C, Dong Y, & Liu W (2010) Analyses of CO2 emissions embodied in Japan-China trade. *Energy Policy* 38(3):1510-1518.
6. Peters GP, Minx JC, Weber CL, & Edenhofer O (2011) Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences* 108(21):8903.
7. Weber CL & Matthews HS (2007) Embodied environmental emissions in US international trade, 1997-2004. *Environmental Science & Technology* 41(14):4875-4881.
8. Wiedmann T, Lenzen M, Turner K, & Barrett J (2007) Examining the global environmental impact of regional consumption activities—Part 2: Review of input–output models for the assessment of environmental impacts embodied in trade. *Ecological Economics* 61(1):15-26.
9. Streets D, *et al.* (2003) An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. *J. Geophys. Res* 108(D21):8809.
10. Zhang Q, *et al.* (2009) Asian emissions in 2006 for the NASA INTEX-B mission. *Atmospheric Chemistry and Physics* 9(14):5131-5153.
11. CSY (2001~2010) *China Statistical Yearbook* (China Statistics Press, Beijing).
12. IEA (2011) *CO2 emissions from fuel combustion hightlights (2011 Edition)* (International Energy Agency, Paris, France).
13. Auvray M & Bey I (2005) Long-range transport to Europe: Seasonal variations and implications for the European ozone budget. *Journal of Geophysical Research-Atmospheres* 110(D11):D11303.
14. Ohara T, *et al.* (2007) An Asian emission inventory of anthropogenic emission sources for the period 1980? 2020. *Atmospheric Chemistry and Physics Discussions* 7(3):6843-6902.
15. Bond TC, *et al.* (2007) Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850-2000. *Global Biogeochemical Cycles* 21(2):Gb2018.
16. Davis SJ & Caldeira K (2010) Consumption-based accounting of CO2 emissions. *Proceedings of the National Academy of Sciences* 107(12):5687-5692.
17. Weber CL, Peters GP, Guan D, & Hubacek K (2008) The contribution of Chinese exports to climate change. *Energy Policy* 36(9):3572-3577.
18. Lu Z, Zhang Q, & Streets DG (2011) Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996–2010. *Atmos. Chem. Phys* 11(18):9839-9864.
19. IPCC (1996) IPCC guidelines for national greenhouse gas inventories. *Reference Manual* 3.
20. Klimont Z, *et al.* (2009) Projections of SO2, NOx and carbonaceous aerosols emissions in Asia. *Tellus B* 61(4):602-617.
21. Lei Y, Zhang Q, Nielsen C, & He K (2011) An inventory of primary air pollutants and CO2 emissions from cement production in China, 1990–2020. *Atmospheric Environment* 45(1):147-154.
22. IOTC (2005,2007,2010) *Input-Output Table of China* (China Statistics Press, Beijing).
23. Xiao L & Xu J (2008) An Empirical Analysis on Real Error of RAS Method. *Mathematics in Practice and Theory*.
24. CESY (2001~2010) *Chinese Energy Statistical Yearbook* (China Statistics Press, Beijing).
25. Zhang Q, *et al.* (2007) NOx emission trends for China, 1995–2004: The view from the ground and the view from space. *J. Geophys. Res* 112:D22306.
26. Guan D, Peters GP, Weber CL, & Hubacek K (2009) Journey to world top emitter: An analysis of the driving forces of China's recent CO2 emissions surge. *Geophysical Research Letters* 36(4):L04709.
27. CISS (2001~2010) *China Iron and Steel Statistics* (China Steel Industry Association, Beijing).
28. Association CC (2001~2010) *China Cement Almanac* (China Building Material Press).
29. CVECAR (2010) China Vehicle Emission Control Annual Report. (Ministry of Environmental Protection of the People's Republic of China).

30. Streets DG, *et al.* (2006) Revisiting China's CO emissions after the Transport and Chemical Evolution over the Pacific (TRACE-P) mission: Synthesis of inventories, atmospheric modeling, and observations. *Journal of Geophysical Research* 111(D14):D14306.
31. He K, *et al.* (2005) Oil consumption and CO2 emissions in China's road transport: current status, future trends, and policy implications. *Energy Policy* 33(12):1499-1507.
32. YBCTC (2007) *Year Book of China Transportation and Communications* (China Stat. Press, Beijing).
33. Zhao Y, *et al.* (2008) Primary air pollutant emissions of coal-fired power plants in China: Current status and future prediction. *Atmospheric Environment* 42(36):8442-8452.
34. Zhao Y, Nielsen C, Lei Y, McElroy M, & Hao J (2011) Quantifying the uncertainties of a bottom-up emission inventory of anthropogenic atmospheric pollutants in China. *Atmospheric Chemistry and Physics* 11(5):2295-2308.
35. Xu Y, Williams RH, & Socolow RH (2009) China's rapid deployment of SO2 scrubbers. *Energy Environ. Sci.* 2(5):459-465.
36. Xu Y (2011) Improvements in the operation of SO2 scrubbers in China’s coal power plants. *Environmental Science & Technology*.
37. Lin J, *et al.* (2010) Recent Changes in Particulate Air Pollution over China Observed from Space and the Ground: Effectiveness of Emission Control. *Environmental Science & Technology* 44(20):7771-7776.
38. MEP (2001~2010) *China statistical yearbook on environment* (China Statisitc Press).
39. Bond TC, *et al.* (2004) A technology-based global inventory of black and organic carbon emissions from combustion. *J. Geophys. Res.* 109(D14203).
40. CTEESY (2001~2010) *China Trade and External Economic Statistical Yearbook* (China Statistics Press, Beijing).
41. Lin JT & McElroy MB (2011) Detection from space of a reduction in anthropogenic emissions of nitrogen oxides during the Chinese economic downturn. (Translated from English) *Atmospheric Chemistry and Physics* 11(15):8171-8188 (in English).
42. Lin J (2012) Satellite constraint for emissions of nitrogen oxides from anthropogenic, lightning and soil sources over East China on a high-resolution grid. *Atmos. Chem. Phys.* 12:2881-2898.
43. Lin JT, McElroy MB, & Boersma KF (2010) Constraint of anthropogenic NOx emissions in China from different sectors: a new methodology using multiple satellite retrievals. *Atmospheric Chemistry and Physics* 10(1):63-78.
44. Liu W, Wang Y, & Ye J (2010) CO2 emissions embodied in international trade of China, 1997–2007. in *International Conference on Management Science and Engineering - ICMSE* (IEEE), pp 1906-1910.
45. Shui B & Harriss RC (2006) The role of CO2 embodiment in US–China trade. *Energy Policy* 34(18):4063-4068.
46. Du H, *et al.* (2011) CO2 emissions embodied in China-US trade: Input-output analysis based on the emergy/dollar ratio. *Energy Policy*.
47. Lin JT & McElroy MB (2010) Impacts of boundary layer mixing on pollutant vertical profiles in the lower troposphere: Implications to satellite remote sensing. *Atmospheric Environment* 44(14):1726-1739.
48. Lin JT, Youn D, Liang XZ, & Wuebbles DJ (2008) Global model simulation of summertime US ozone diurnal cycle and its sensitivity to PBL mixing, spatial resolution, and emissions. *Atmospheric Environment* 42(36):8470-8483.
49. Kuhns H, Green M, & Etyemezian V (2003) Big Bend Regional Aerosol and Visibility Observational (BRAVO) Study Emissions Inventory. (Desert Research Institute, Las Vegas, NV 89119).
50. Klimont Z, *et al.* (2002) Anthropogenic emissions of non-methane volatile organic compounds in China. *Atmospheric Environment* 36(8):1309-1322.
51. Statistics NBo (2001, 2006) *China Industrial Economy Statistical Yearbook* (China Statistic Press, Beijing).