Atmos. Chem. Phys. Discuss., 14, 25617–25650, 2014
www.atmos-chem-phys-discuss.net/14/25617/2014/
doi:10.5194/acpd-14-25617-2014

Atmospheric Chemistry and Physics Discussions
Open Access

This discussion paper is/has been under review for the journal Atmospheric Chemistry and Physics (ACP). Please refer to the corresponding final paper in ACP if available.

Assessment of China's virtual air pollution transport embodied in trade by a consumption-based emission inventory

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Received: 24 July 2014 – Accepted: 15 September 2014 – Published: 9 October 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

High anthropogenic emissions from China have resulted in serious air pollution, and it has attracted considerable academic and public concern. The physical transport of air pollutants in the atmosphere has been extensively investigated, however, understanding the mechanisms how the pollutants were transferred through economic and trade activities remains challenge. In this work, we assessed China's virtual air pollutant transport embodied in trade, by using consumption-based accounting approach. We first constructed a consumption-based emission inventory for China's four key air pollutants (primary $PM_{2.5}$, sulfur dioxide (SO_2), nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOC)) in 2007, based on the bottom-up sectoral emission inventory concerning their production activities – a production-based inventory. We used a multiregional input-output (MRIO) model to integrate the sectoral production-based emissions and the associated economic and trade activities, and finally obtained consumption-based inventory. Unlike the production-based inventory, the consumption-based inventory tracked emissions throughout the supply chain related to the consumption of goods and services and hereby identified the emission flows followed the supply chains. From consumption-based perspective, emissions were significantly redistributed among provinces due to interprovincial trade. Large amount of emissions were embodied in the net imports of east regions from northern and central regions; these were determined by differences in the regional economic status and environmental policies. We also calculated the emissions embodied in exported and imported goods and services. It is found that 15–23 % of China's pollutant emissions were related to exports for foreign consumption; that proportion was much higher for central and export-oriented coastal regions. It is suggested that measures should be introduced to reduce air pollution by integrating cross-regional consumers and producers in national agreements to encourage efficiency improvement in the supply chain and optimizing consumption structure internationally. The consumption-based air pollutants

emission inventory developed in this work can be further used to attribute pollution to different economic activities and final demand types with the aid of air quality models.

1 Introduction

China's rapid industrialization since 2000 has been accompanied by large increases in emissions of air pollutants, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC) and black carbon (BC) (Ohara et al., 2007; Lin et al., 2010; Zhang et al., 2009). In turn, the visible degradation of air quality in China has made environmental and health issues a major focus of policy (Yang et al., 2013; Boldo et al., 2006; Bell et al., 2007). The ambient particulate matter is considered as the most substantial health risks in China, having contributed to 1.2 million premature deaths and removing 25 million healthy years of life in 2010 alone (Yang et al., 2013). The related economic costs are also enormous: the human health impacts of PM_{10} in urban areas of China were estimated to be almost 74 billion dollars in 2010 (Yu et al., 2013) – nearly 1.3 % of China's gross domestic product for that year. In response, China's government prepared its Action Plan for Air Pollution Control in September 2013 with the purpose of supporting efforts to reduce air pollution. In this plan, air quality and economic development are of equal importance in assessing the performance of government officials at local, provincial and national levels.

Pollution abatement has to begin with an understanding of pollution sources. Previous researches have therefore focused on bottom-up inventories of pollutant emissions over China, based on energy statistics and datasets of technology in use (e.g., Zhang et al., 2007, 2009; Streets et al., 2003; Lei et al., 2011). These inventories assign emissions to where pollutants are physically produced, which results in production-based pollution accounting. The bottom-up inventories have been extensively used in Chemical transport models to predict and interpret air pollutions, or used to guide the implementation of emission control measures.

As part of efforts to improve air quality, the Chinese government has imposed strict regulations on pollutants emissions in mega-cities. However, if the response is to shift industry out of these cities without changing consumption patterns, the result of the regulations may be an increase in the total amount of pollution emissions and little or no improvement in air quality, since there will be an increase in emissions through transportation along the geographically extended supply chains and also because that the general low efficient production in less regulated areas. For example, roughly one-third of the electricity consumed in Beijing is generated in Inner Mongolia (Liu et al., 2012b). Stricter regulations of the power sector in Beijing will tend to increase the import of electricity if similar actions are not taken in Inner Mongolia. Given this connection, the most cost-effective means of reducing emissions from the power sector in Inner Mongolia might not only be deploying new generation technologies there, but also conserving energy in Beijing – as well as facilitating technological cooperation between these two regions (Liu et al., 2013; Lindner et al., 2013). In this regard, effective and cost-effective management of air quality may therefore require policies that cover the entire supply chain, which in turn will depend upon quantitative understanding of the transport of emissions between producers and consumers.

Indeed, this dynamic consequence has already been demonstrated in the case of CO_2 emissions: high levels of consumption in China's developed coastal regions are driving CO_2 emissions in interior provinces, where CO_2 emission intensity is much greater (Feng et al., 2013). As a result, large quantities of emissions are embodied in the goods traded among provinces, and the less developed regions bear a disproportionate share of the costs for both the pollution and its mitigation. Recent work has demonstrated that the effectiveness of efforts to decrease pollution depend on understanding not only where pollutants are produced, but also where the goods and services related to the pollution are ultimately consumed (Davis and Caldeira, 2010; Davis et al., 2011; Feng et al., 2013; López et al., 2013; Guan et al., 2014a; Lin et al., 2014). However, an effective air quality management system that takes into account the impact of supply chains is still missing because the mechanisms on the transport

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of air pollutant emissions through economic and trade activities are not well established yet.

In this study, we developed a consumption-based air pollutant emission inventory framework to explore the emission flow embodied in supply chains in China. With this framework, we estimated emissions of four air pollutants (primary $PM_{2.5}$ and its key precursors SO_2, NO_x and NMVOC) embodied in goods and services traded among China in 2007. These particles are known to have particularly large impact on health in China's cities (Ma et al., 2011; Chen et al., 2012a, b). We used a multiregional input-output (MRIO) model to reallocate emissions from the provinces where they were produced to the provinces where the related products were ultimately consumed. Given China's substantial international trade, a sizable proportion of pollution is related to goods that are ultimately consumed in other countries. We allocate such emissions to a single "out-of-China" region. To better assess consumption patterns, we also assessed the contribution of four different categories of consumer demand: urban household, rural household, government and capital formation. The consumption-based air pollutant emission inventory developed in this work can then be used to attribute pollution to different economic sectors and final demand types with the aid of air quality models. It should be noted that our consumption-based accounting procedure should not be interpreted as assigning all economic or ethical responsibility for pollution to consumers (Wiedmann, 2009; Davis and Caldeira, 2010; Guan et al., 2014a); it represents a critical source of information for consideration by decision makers, who design public policy accordingly.

This paper is organized as follows: in Sect. 2, we describe key principles of consumption-based accounting and details of our MRIO model, including the sources and treatment of raw economic data. Section 3 presents pollutants emissions embodied in traded products and consumption-based emissions at provincial level. Section 4 discuss the possible impacts of current policies according to our finding and related policy implication.

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2 Methodology and data

2.1 MRIO analysis

Since developed by Leontief (1970), environmental extended input-output analysis has been widely used to analyze the drivers and causes of global and regional environmental changes in many different contexts (Wiedmann et al., 2007; Hertwich and Peters, 2009; Minx et al., 2009; Suh, 2009). In the past several years, environmental extended MRIO models have been developed to quantify global CO_2 emissions embodied in international trade, initially for a specific year (Davis and Caldeira, 2010), and later over multiple years (Peters et al., 2011). More recently, sectoral resolution of an input-output table has been improved to allow MRIO analysis among 187 countries and 15909 sectors (Lenzen et al., 2012, 2013). Liu et al. (2012) developed a MRIO model that consist of 30 sectors and 30 provinces in China, and have been widely used to assessing CO_2 emissions embodied in trade flows among China and internationally in 2007 (Feng et al., 2013). Here, we apply this Chinese MRIO in 2007 to quantify non-CO_2 air pollutants embodied in goods and service traded among China's provinces and internationally. We summarize the model and data sources bellow.

The Chinese MRIO framework begins with the accounting balance of monetary flows:

$$\boldsymbol{x}^r = \mathbf{A}^{rr}\boldsymbol{x}^r + \boldsymbol{y}^{rr} + \sum_{s \neq r} \mathbf{A}^{rs}\boldsymbol{x}^s + \sum_{s \neq r} \boldsymbol{y}^{rs} + \boldsymbol{y}^{re} \quad (1)$$

Here, r and s indicate province r (producer) and s (consumer); $\boldsymbol{x}^r$ and $\boldsymbol{x}^s$ are, respectively, the vectors for sectoral total outputs in province r and s; $\mathbf{A}^{rr}x^r$ represents the industry requirements to produce its regional final products and $\mathbf{A}^{rr}$ is a matrix with its columns representing specific sectors' local inputs required to produce one unit output; $A^{rs}x^s$ and A^{rs} represents the cross-regional industry requirement import from province r to province s and its coefficients to produce one unit output; $\boldsymbol{y}^{rr}$ is a vector with its elements representing final consumption (urban and rural household, government and

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capital formation) produced in province r; $\boldsymbol{y}^{rs}$ is the cross-regional final products supply from province r to s; and $\boldsymbol{y}^{re}$ is a vector indicating region $r's$ sectoral products for international export. Evaluating the equation for all sectors and all provinces, we construct a matrix that represents the entire Chinese domestic economy, including its export:

$$\begin{pmatrix} x^1 \\ x^2 \\ \vdots \\ x^m \end{pmatrix} = \begin{pmatrix} A^{11} & A^{12} & \cdots & A^{1m} \\ A^{21} & A^{22} & \cdots & A^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A^{m1} & A^{m2} & \cdots & A^{mm} \end{pmatrix} \begin{pmatrix} x^1 \\ x^2 \\ \vdots \\ x^m \end{pmatrix} + \begin{pmatrix} \sum_r y^{1r} + y^{1e} \\ \sum_r y^{2r} + y^{2e} \\ \vdots \\ \sum_r y^{mr} + y^{me} \end{pmatrix} \quad (2)$$

Here m indicate the total region's number, and $m = 30$ in this research.

When solved from the total output, Eq. (2) can yield the following:

$$\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} \quad (3)$$

The uppercase letters in Eq. (3) represent the corresponding matrixes in Eq. (2). $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix.

Pollutant emissions (here refers to primary $PM_{2.5}$, SO_2, NO_x and NMVOC, see Sect. 2.4 below) are then calculated by incorporating a vector of emission intensity:

$$\mathbf{E} = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} \quad (4)$$

where F is the direct emission intensity vector calculated by each sector's total emissions divided by that sector's total output X from Eq. (3) (Hubacek and Sun, 2005; Lin et al., 2014).

2.2 Emissions embodied in interprovincial and international trade flows

Using the pollution emissions calculated by the Chinese MRIO, we quantify the emissions embodied in trade flows among China's provinces and in trade between those provinces and other countries. By disaggregating the final demand of each province in Eq. (4), we could quantify emissions of each pollutant embodied in the goods and services consumed in each provinces as well as where the emissions were produced. For example, the final demand of province r is $y_c^r = (y^{1r} \quad y^{2r} \cdots y^{rr} \cdots y^{mr})'$, and it includes products produced in province r (y^{rr}) as well as final products imported from other regions ($\sum_{s \neq r} y^{sr}$). Using this vector as **Y** in Eq. (4) gives the emissions embodied in the final consumption of province r:

$$E_c^r = \sum_{s=1} E_c^{sr} = \sum_{s=1} f^s (I - A)^{-1} y_c^r \quad (5)$$

where $\boldsymbol{F}^s$ is a vector of the corresponding sectoral pollution intensities for region s but zeros for all other; E_c^r represents total pollutant emissions embodied in region r's consumption that were produced within China; it excludes emissions embodied in any interprovincial exports, and includes imports (E_c^{sr}, $r \neq s$). The solution is region and sector specific.

Pollutants embodied in international exports can be calculated by isolating the demand Y for exports, y^e:

$$E_e = \sum_{r=1} E_e^r = \sum_{r=1} f^r (I - A)^{-1} y^e \quad (6)$$

here E_e^r indicates province r's emission embodied in international exports.

We also attempt to estimate the emissions embodied in international imports. We begin with a simplifying assumption that imported products were produced under the same industrial structure and technology in China (Tang et al., 2012). This gives emissions avoided by import (EAI):

$$E_{\mathrm{EAI}} = \sum_{r=1} E_{\mathrm{EAI}}^r = F (I - A)^{-1} y^{\mathrm{Im}} \quad (7)$$

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To obtain the pollution embodied in each province's imports, we assume that China's total import form nation i was proportionally distributed to each province; then we adjusted the EAI of each province by a coefficient, u_r, which reflects the producing nations' average pollution intensity (Lin et al., 2014):

$$\mu_r = \sum_i \frac{\mathrm{NI}_i}{\mathrm{PI}_r} \times \frac{N_i^{\mathrm{exp}}}{C^{\mathrm{tim}}} \quad (8)$$

NI_i indicates nation i's pollutant intensity; PI_i signifies province r's pollutant intensity; N_i^{exp} indicates nation i's total export to China; C^{tim} signifies China's total import. Thus, the emission embodied in international imports to province r is $\mu_r E_{\mathrm{EAI}}^r$.

As in the study by Liu et al. cited above, the data required for Chinese MRIO were derived from provincial input-output tables (National Bureau of Statistics, 2011). The trade data between China and the other countries used in this section for China's international trade were aggregated from the China Foreign Economic Statistical Yearbook (National Bureau of Statistics, 2008a) and the China Trade and Economic Statistical Yearbook (National Bureau of Statistics, 2008b). Provincial input-output tables (National Bureau of Statistics, 2011) were used to supplement and modify the international import data.

2.3 Consumption-based emissions by province

Consumption-based emissions represent the quantities of pollution related to all the goods and services consumed by a given province (Peters, 2008; Peters and Hertwich, 2008; Davis and Caldeira, 2010; Lin et al., 2014). The gross flows of emissions embodied in trade can thus be used to quantify consumption-based emissions – by adding emissions embodied in imports to and subtracting emissions embodied in exports from the emissions physically produced in each province:

$$\mathrm{CE} = \mathrm{PE} - \mathrm{INE} - \mathrm{IPE} + \mathrm{INI} + \mathrm{IPI} \quad (9)$$

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CE and PE indicate regional pollution inventories under the consumption and production perspectives, respectively; INE and INI signify the emissions embodied in international exports and imports, respectively; IPE and IPI indicate emission embodied in interprovincial exports and imports.

2.4 Production-based inventory data

The vector of pollution intensity, $\boldsymbol{F}$, in Eqs. (4 and 7) is derived from the multi-resolution emission inventory for China (MEIC: http://www.meicmodel.org) compiled by Tsinghua University. The MEIC is a production-based inventory, updated from the widely used INTEX-B dataset (Zhang et al., 2009). The inventory covers 31 provinces or autonomous regions, 10 pollutants (e.g., SO_2, NO_x, CO, NMVOC, BC, $PM_{2.5}$, PM_{10}, Ammonia (NH_3), organic carbon (OC), and CO_2) and ~ 700 emitting sources categories. In this study, we used the energy balance table of each province from the China Energy Statistical Yearbook (National Bureau of Statistics, 2008c) and the revised sectoral energy consumption from China Economic Census Yearbook (National Bureau of Statistics, 2010) to map the MEIC emission data onto the sectors in our Chinese MRIO (Guan et al., 2014b). The sector classification appears in Appendix A1 (the total 30 sectors had been aggregated into 27 sectors allowing for the consistency between MRIO and emission sectors). Global emissions were taken from EDGAR v.4.2 (http://edgar.jrc.ec.europa.eu/) to calculate aggregated pollution intensities of other countries (see Eq. 8).

3 Results

3.1 Production-based pollution emissions

Figure 1 presents the source contribution to production-based Chinese emissions for the four air pollutants (primary $PM_{2.5}$, SO_2, NO_x and NMVOC) in 2007. In 2007, primary $PM_{2.5}$ emissions amounted to 13.25 Tg, mainly from industrial processes (45 %)

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and residential activity (33 %). Specifically, cement production accounted for 21 % of the total emission, and traditional biomass-burning stoves used in rural households accounted for 26 %. Total SO_2 emissions in 2007 were 32.60 Tg, primarily from fossil fuel combustion for power and heating (51 %) and manufacturing sectors (35 %). 24.88 Tg NO_x emitted in 2007 derived mostly from power and heating (41 %), industrial energy use (28 %) and mobile source (27 %). NMVOC emissions amounted to 20.53 Tg in 2007; they were dominated by emissions from industrial processes (48 %, e.g., oil refining and chemical manufacturing), residential activities (25 %) and mobile source (16 %).

3.2 Emission contributed by final demand categories

According to the input-output analysis, final demands are divided into five categories: urban households consumption, rural households consumption, government consumption, capital formation and export. For the emission caused by domestic rural and urban residential direct consumption (i.e. the residential emissions in Fig. 1), they were listed as independent final categories as they are irrelevant to economic production system, and named as rural_direct and urban_direct in this research.

Nationally, we found that capital formation was the largest triggering factor for Chinese emissions in 2007, accounting for 43, 48, 52 and 33 % of the country's total consumption-based emissions for primary $PM_{2.5}$, SO_2, NO_x and NMVOC, respectively. The urban household consumption of goods and services was the second largest driver of China's pollutants in 2007, the related production emissions caused by this consumption accounting for 13–29 % of national consumption-based emissions. Rural household consumption-related production emissions accounted for 5–9 % of total national consumption emissions, and governmental consumption accounted for 4–9 % of total national consumption emissions. For primary $PM_{2.5}$ and NMVOC, considerable proportions (33 and 25 %, respectively) derived from direct rural residential energy consumption activities, particularly through biofuel combustion in the traditional stoves.

Figure 2 presents pollutant emissions caused by each final consumption category among the 30 provinces. Capital formation and urban residential consumption dominated the consumption-based emission of SO_2 and NO_x in all the provinces, which reflects the large-scale nationwide expansion of infrastructure. The capital formation of Shandong contributed most to national consumption-based SO_2 (5 %) and NO_x (3 %) emissions; this was followed by Jiangsu (3 % for SO_2 and 4 % for NO_x), Zhejiang (3 % for SO_2 and 4 % for NO_x) and Guangdong (3 % for SO_2 and 4 % for NO_x).

For primary $PM_{2.5}$ and NMVOC, capital formation and direct rural residential energy consumption dominated the total consumption-based emissions in almost all provinces. In Beijing, Jiangsu, Shanghai, Zhejiang and Guangdong, biomass combustion is not used as a significant energy source; thus, capital formation and urban residential consumption activities dominated those regions' total consumption-based emissions. For less developed regions, such as Guangxi, Guizhou, Anhui and Sichuan, biofuel is still be an important energy source, so the related combustion emission accounts for over 50 % of regional consumption-based emissions for primary $PM_{2.5}$ and NMVOC.

3.3 Consumption-based pollution by province

Table 1 compares the production-based and consumption-based pollution emissions in 2007 for all 30 provinces in mainland China. Tibet is excluded in this work due to lack of MRIO data. In Anhui, Sichuan and Guangxi, total emissions are similar with the two accounting methods, which indicate that substantial proportions of the goods produced in these provinces were consumed locally. In these provinces, emissions were largely related to residential direct energy consumption (accounted for here as the emission service for regional consumption). In provinces whose economy is dependent on energy generation, heavy industry, or materials manufacturing, production-based emissions were much greater than consumption-based emissions. For example, in Hebei, 63 % of primary $PM_{2.5}$, 67 % of SO_2, 68 % of NO_x and 56 % of NMVOC emissions were related to products consumed outside that province. Similarly, consumption-based emis-

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sions in Shanxi and Inner Mongolia were 26–62 % lower than production-based emissions. This difference indicates that over 50 % of their total pollutants emissions were embodied in producing interprovincially or internationally exported products. For the provinces where service industries and light industries highly developed, consumption-based emissions were greater than production-based emissions since they are highly dependent on products or energy imported from other provinces. For example, Beijing's consumption-based emissions are 2.6-, 3-, 1.6- and 1.5-fold its consumption-based emissions for primary $PM_{2.5}$, SO_2, NO_x and NMVOC, respectively; about 74–83 % of its consumption-based emission were imported.

3.4 Emissions embodied in interprovincial trade flows

Figure 3 shows the balance of air pollutants embodied in products traded among the 30 provinces in 2007. Nationally, 3.06 Tg of primary $PM_{2.5}$ (23 % of total Chinese production-based emission), 10.53 Tg of SO_2 (33 %), 7.62 Tg of NO_x (31 %) and 4.66 Tg of NMVOC (23 %) are emitted during the production of products or service that are ultimately consumed in other provinces or regions in China. Economically advanced regions, such as Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang and Guangdong were net importers of emissions, whereas, areas of heavy industry or manufacturing bases, such as Hebei, Shanxi, Henan, Inner Mongolia and Shannxi are net exporters of emissions.

Pollutants embodied in intermediate products make up a large portion of the pollutants embodied in interprovincial trade. This indicates that most of the goods being traded had supply chains that covered multiple provinces, with relatively few products being entirely manufactured in one province for consumption in local region. This indicates a strengthened interregional cooperation in manufacturing pattern. For emissions embodied in exports, the ration between finished goods and intermediate goods varies from 1 : 1 to 1 : 12 across the provinces. The lowest ratio is 1 : 12 for Shanxi, which exported large amounts of energy to Beijing, Tianjin and some regions in southern China. The finished-to-intermediate ratio of emissions embodied in imports was similarly vari-

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able, ranging from 1 : 1 to 1 : 13. The lowest ratio amounted to 1 : 13 for Zhejiang, which imported large volumes of intermediate products from the Central, North and Northwest regions to support its local industries.

Figure 4 presents the largest net flows of embodied pollutants among the eight regions (listed in Table A2 in Appendix A). From the perspective of technology development, there was an increasing trend in pollutant intensity from southeast to northwest China for all the four pollutants. The Northeast had the highest emission intensity for SO_2 (223 Mg 100 million CNy^{-1}), NO_x (145 Mg 100 million CNy^{-1}) and NMVOC (74 Mg 100 million CNy^{-1}); the Central region had the highest primary $PM_{2.5}$ emission intensity (50 Mg 100 million CNy^{-1}); South Coast had the lowest SO_2 (39 Mg 100 million CNy^{-1}) and NO_x (49 Mg 100 million CNy^{-1}) emission intensity; Beijing-Tianjin had the lowest $PM_{2.5}$ (13 Mg 100 million CNy^{-1}) and NMVOC (41 Mg 100 million CNy^{-1}) emission intensity. In terms of pollution transfer, affluent areas, such as the Beijing-Tianjin, East Coast and South Coast regions, were net pollution importers owing to their relatively advanced economic development and modernized production technologies (and thus lower pollution intensity). For example, primary $PM_{2.5}$ emissions embodied in imports to the East Coast region are four times higher much than those embodied in exports; the figures for SO_2, NO_x and NMVOC are 3-, 2- and 1.5-fold, respectively. About 80 % of the emissions embodied in East Coast's imports occur in the North, Central and Northeast regions. In Beijing-Tianjin, the pollutants embodied in imports exceeded those embodied in exports by factors of 4.5, 4, 3 and 2 for primary $PM_{2.5}$, SO_2, NO_x and NMVOC, respectively. Further, 46 % of the primary $PM_{2.5}$, 27 % of SO_2, 28 % of NO_x and 24 % of NMVOC embodied in Beijing-Tianjin's imports derived from the North region (including Hebei and Shandong). In contrast, less economically developed areas in the North, Central, Northwest and Southwest regions were net exporters, with large quantities of emissions outsourced by East and South Coast regions.

3.5 Emissions embodied in international trade flows

Large share of air pollution in China is embodied in international exports. About 2.04 Tg of primary $PM_{2.5}$ (15 % of total Chinese production-based emission), 6.96 Tg of SO_2 (21 %), 5.72 Tg of NO_x (23 %) and 4.32 Tg of NMVOC (21 %) are embodied in goods or services exported internationally. In contrast, much less pollution was embodied in goods imported to China from other countries: it accounted for only about 25 % of the emissions embodied in Chinese exports for primary $PM_{2.5}$, SO_2 and NO_x, and for about 50 % for NMVOC. This difference suggests that China may be producing a large share of the emissions-intensive goods consumed worldwide or that its production processes are dirtier that those imported ones (Lin et al., 2014). Simultaneously, China's greater volume of exports over imports may also largely contribute to this major pollution surplus (Su and Ang, 2011). Since China joined the World Trade Organization (WTO), the proportions of net exports account for total exports of China had increased from 8 % in 2001 to 22 % in 2007, mainly contributed by manufactured products export (National Bureau of Statistics, 2013). Even though the proportion decreased in recent years, the gross ratio for manufactured products exports is still on the rise.

Figure 5 presents the emissions embodied in internationally traded products at the provincial level. In keeping with China's role as the world's largest exporter, most provinces have a trade deficit in embodied emissions. From the perspective of absolute, most of the coastal regions have high pollutant exports than inland provinces. Shandong was the largest exporter with 260.04 Gg of primary $PM_{2.5}$, 833.07 Gg of SO_2, 686.77 Gg of NO_x and 469.81 Gg of NMVOC embodied in international exports; those emissions accounted for 11–13 % of the total emissions embodied in China's international exports. Other major exporting provinces included Guangdong, Hebei, Zhejiang and Jiangsu. Total pollutants export of these five largest exporters accounted for 41, 37, 46 and 52 %, respectively, of the national total. The emissions embodied in Guangdong's imports were the largest among all the provinces (77.47 Gg primary $PM_{2.5}$, 344.81 Gg SO_2, 229.79 Gg NO_x and 530.67 Gg NMVOC), accounting for 16,

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18, 16 and 21 % of China's total imports of primary $PM_{2.5}$, SO_2, NO_x and NMVOC, respectively, followed by Shanghai, Jiangsu, Zhejiang and Beijing.

A province may make a final product for international export, but it can also make an intermediate product for another province's international export. The former process leads to emissions embodied in direct international export, whereas the latter leads to emissions associated with other regions' international export. The ratios of these two types of emissions range from 0.2 : 1 to 10 : 1. The leading ratios were found in coastal manufacturing hubs: Guangdong was highest (10 : 1, 8 : 1, 9.5 : 1 and 7 : 1 for primary $PM_{2.5}$, SO_2, NO_x and NMVOC, respectively), and it was followed closely by Shanghai, Fujian, Zhejiang, Jiangsu and Tianjin. The lowest ratios occur in the distant interior province of Inner Mongolia (0.2 : 1, 0.2, 0.2 : 1 and 0.3 : 1), followed by Guizhou (0.3 : 1, 0.3 : 1, 0.3 : 1 and 0.4 : 1).

The international exports from the coastal areas consist of Guandong, Fujian, Shanghai, Zhejiang, Jiangsu, Tianjin and Shandong accounts for 82 % of all Chinese exports. However, the associated embodied emissions were only 43, 41, 52 and 60 % of China's total export-embodied emissions for primary $PM_{2.5}$, SO_2, NO_x, and NMVOC, respectively. The disparity between the export volume of these regions and their embodied pollutants in part reflects the regions' high economic development and pollution intensity being lower than the national average. From the embodied perspective, the pollution embodied in these regions' export account for 68, 69, 73 and 75 % of the national total for primary $PM_{2.5}$, SO_2, NO_x, and NMVOC, respectively. These are much close to the monetary export share, suggesting a high rely on intermediate products from the Central and West regions of China (Feng et al., 2013), which embodied more emissions.

Figure 6 shows the largest cross-regional flows of emissions embodied in intermediate products caused by international exports production by the eight regions, and it supports the conjecture in previous paragraphs. We found that, even though the east regions (including East Coast, South Coast and Beijing-Tianjin) had enormous pollutants exported, considerable amounts of extra emissions were embodied in their inter-

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national exports originally occur in Central, Northwest and Southwest regions: these emission accounted for approximately 50 % of the later regions' total international exported pollutants.

4 Discussion

4.1 Importance of international and interprovincial transfer in pollutants

The results indicate the substantial leakage of emission from foreign countries to China via international trade. The pollution embodied in international trade accounted for 15–23 % of total pollutants emission produced in China. Furthermore, 41–60 % of the embodied emissions occurred in Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian and Guangdong, all of which are located in the China's three biggest industrial bases (Jing-Jin-Ji, Yangtze River delta and Pearl River delta) and where air pollutions is severe. Allow for the embodied emission from other regions, the pollution embodied in these regions' products exports accounts more (68–75 %). Thus, reduction policies related to export adjustment should tend to focus on these key export-oriented regions, as well as the exported products that involve multi-sector and multi-regional supply chains but with low add valve (Skelton et al., 2011 Skelton, 2013). An economic stimulus or penalty instigated by an export-oriented company can help reduce the emissions of its suppliers, thereby exerting a cleaning effect on its upstream supply chains (Skelton, 2013).

Domestically, interprovincial trade is accompanied by substantial pollutant transfer, which is more significant than with international trade. As shown in Fig. 3, 23, 33, 31 and 23 % (3.06, 10.54, 7.62 and 4.66 Tg), respectively, of China's primary $PM_{2.5}$, SO_2, NO_x and NMVOC are related to goods or services that are ultimately consumed outside of the provinces where they were produced. Most of this pollutants transfer occurs between developing central and western regions and the affluent east coastal regions.

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Recently, China's central government has launched nationwide acts to reduce the CO_2 emission (Liu et al., 2012b) and atmospheric pollutants (The State Council of the PRC, 2013), with stricter measures being implemented for eastern than western provinces. This disparity in mitigation targets is likely to accelerate the relocation of heavy industries to central and west regions, thereby worsening the atmospheric environment in those less developed regions. As evident in Fig. 4, the production-related pollutant intensities of the eight regions showed a gradually increasing trend from the developed southeast to less developed northwest regions. This means that more pollutants were emitted to make one product unit in central and west regions. Relocating industries will thus redistribute the environmental problem rather than eliminate it – aka the "beggar-thy-neighbor" effect. Increasing interprovincial trade will also drive traffic flows, which have been a key contributor to atmosphere pollutants emissions (Cheng et al., 2013). Thus this kind of industrial shift may ultimately increase total national pollutant emissions to some extent.

Furthermore, since air pollutants can be transported over a great distance in the atmosphere (Lin et al., 2014), the richer east would likely to face even more severe pollution originating outside its jurisdiction, as a consequences of policy and economic stimulus (Ying et al., 2014). To avoid this problem, an effective pollution control strategy would target a reduction in total pollution rather than simply relocating emissions. It would be better to locate industries according to regional characteristic, considering access to material and transportation factors. Technology transfer between developed and developing regions should play a leading role in joint actions for regional or interregional air pollution control. Appropriate regional industrial layout play a critical role in regional industrial development and environmental conditions.

4.2 Impact of consumption pattern

Emissions related to urban residential goods and services consumption accounted for about 25 % of all China's consumption-based pollutants analyzed in this study; rural residential only accounted for 5–9 %; construction-dominated capital formation account

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for 50 %. However, China's proportion of urbanization increased from 26.4 % in 1990 to 53.4 % in 2013, and it is expected to be 65 % in 2030 (China Development Research Foundation, 2010). This rapid urbanization has created a boom in the demand for materials and infrastructure; it has greatly accelerated industrial production and infrastructure construction – and therefore also the related pollutant emissions (Heinonen and Junnila, 2011). Recently, the implementation of the "New Socialist Countryside" which is aimed to improve living condition in countryside by unify planning and constructing, will result in a wave on construction in rural areas nationwide. This rapid construction will drive the exploration and production of natural resources as well as related pollution emissions. In addition, the average life span of building in China is 35 years – much less than the 74 years of the United States and 132 years of the UK (China Economic Review, 2013). Rapid increasing in construction will aggravate this phenomenon.

Recent studies have shown that China's current technology improvements will be barely able to offset the pollution emissions associated with increasing consumption (Liang et al., 2013; Guan et al., 2014b). However, China's government has to continue to promote the economic growth to improve livelihoods and defeat environmental problem. Thus, to achieve pollution reduction targets, the government needs to focus on key source sectors and technologies; however, it also need to pay greater attention to control and management strategies with respect to consumption. Our study indicates that, the key regulatory policies should focus on construction sector, such as promoting the use of energy-saving building materials, increasing the life span of building, thus decrease the related upstream emissions along the supply chains. Simultaneously, advocating saving behaviors in daily life is also essential.

Our MRIO analysis traced pollutant sources related to consumption activities. It clearly illustrates the extent and structure of externalization of pollutants, and it presents a reasonable approach to facilitating collaboration between producers and consumers. This approach appears to present an effective way to optimize air quality management decisions toward environmentally sustainable economic growth. Future work can link our provincial level consumption-based inventory and the pollution flows with chemical transport models, to investigate the impacts of trade activities on regional and global air quality.

Acknowledgement. This study was supported by China's National Basic Research Program (2014CB441301) and the National Science Foundation of China (41222036, 71322304, 41328008, 41175127 and 71341025). Q. Zhang and K. B. He are supported by the Collaborative Innovation Center for Regional Environmental Quality.

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Table 1. Comparison of regional pollutant emissions from production and consumption-based emissions (Gg year^{-1}).

Pollutant	Primary $PM_{2.5}$		SO_2		NO_x		NMVOC	
Region	Pro	Con	Pro	Con	Pro	Con	Pro	Con
Beijing	111	285	261	775	385	629	372	571
Tianjin	127	183	429	548	361	445	286	326
Hebei	974	513	2347	1387	1780	1036	1199	842
Shandong	1276	933	3105	2375	2582	1940	1948	1554
Liaoning	587	416	1189	826	1250	850	900	668
Jilin	316	338	513	735	650	723	512	493
Heilongjiang	370	363	367	475	786	640	705	589
Shanghai	142	338	726	1112	591	838	557	836
Jiangsu	680	689	1544	1375	1777	1356	1571	1339
Zhejiang	368	548	957	1371	1231	1291	1113	1008
Shanxi	755	435	2483	1241	1148	593	653	486
Henan	1015	667	1532	1157	1685	1108	1176	1032
Anhui	555	515	718	667	871	674	812	759
Hubei	542	481	1674	1248	862	695	768	751
Hunan	544	441	1353	1045	730	646	595	556
Jiangxi	286	286	701	906	455	589	348	378
Fujian	261	221	586	516	525	453	430	422
Guangdong	629	669	963	1642	1494	1361	1541	1487
Hainan	34	37	91	82	84	75	100	78
Guangxi	484	439	970	674	467	406	706	643
Chongqing	249	270	1307	1037	367	388	317	353
Sichuan	771	764	1560	1415	747	747	1112	1093
Guizhou	424	318	1841	812	545	302	346	313
Yunnan	383	322	837	628	551	410	462	461
Inner Mongolia	352	281	1680	858	555	450	521	423
Shaanxi	218	197	414	352	370	274	329	287
Gansu	58	48	77	101	92	103	68	70
Qinghai	83	74	519	303	242	167	95	104
Ningxia	214	206	473	447	479	405	445	307
Xinjiang	436	282	1386	570	1182	448	541	384

Pro = production-based emissions; Con = consumption-based emissions.

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Table A1. Sectors classification for MRIO Table.

Sector number	Sector Name
1	Agriculture
2	Coal mining and processing
3	Crude petroleum and natural gas products
4	Metal ore mining
5	Non-ferrous mineral mining
6	Manufacture of food products and tobacco processing
7	Textile goods
8	Wearing apparel, leather, furs, down and related products
9	Sawmills and furniture
10	Paper and products, printing and record medium reproduction
11	Petroleum processing and coking
12	Chemicals
13	Nonmetal mineral products
14	Metals smelting and pressing
15	Metal products
16	Machinery and equipment
17	Transport equipment
18	Electric equipment and machinery
19	Electronic and telecommunication equipment
20	Instruments, meters, cultural and office machinery
21	Handicrafts and other Manufacturing
22	Electricity, steam and hot water production and supply
23	Gas and water production and supply
24	Construction
25	Transport and warehousing, Post and telecommunication
26	Wholesale and retail and catering accommodation
27	Others

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Table A2. Region divisions.

Region	Provinces/municipalities that included in each region
Beijing-Tianjin	Beijing and Tianjin
North	Hebei and Shandong
Northeast	Liaoning, Jilin and Heilongjiang
East Coast	Jiangsu, Shanghai and Zhejiang
Central	Shanxi, Henan, Anhui, Hunan, Hubei and Jiangxi
South Coast	Fujian, Guangdong and Hainan
Southwest	Sichuan, Chongqing, Guizhou, Yunnan, Guangxi (and Tibet)
Northwest	Shannxi, Gansu, Qinghai, Ningxia, Xinjiang and Inner Mongolia

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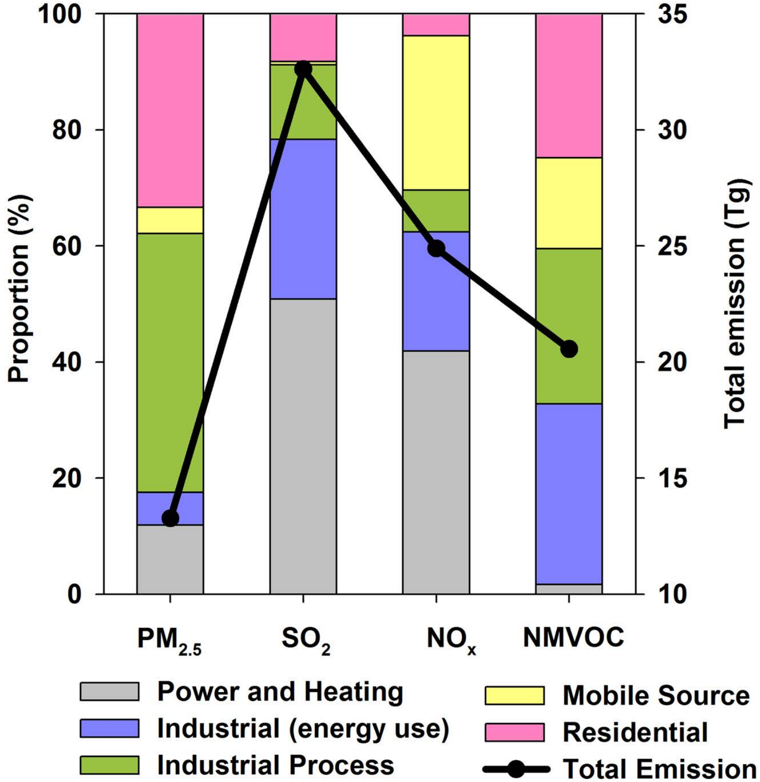

Figure 1. Production-based pollutant emissions by sectors in China in 2007.

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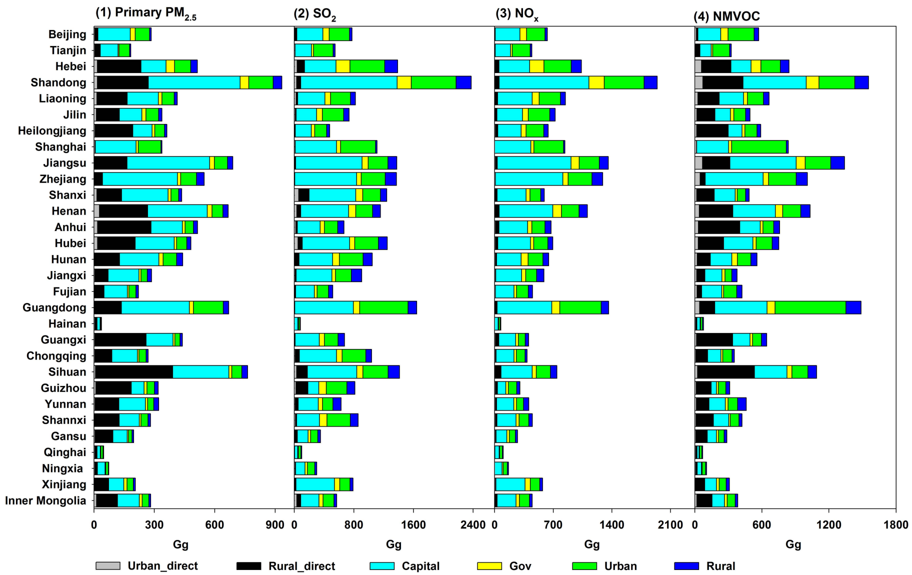

Figure 2. Pollutant emissions embodied in each region's final demand by categories.

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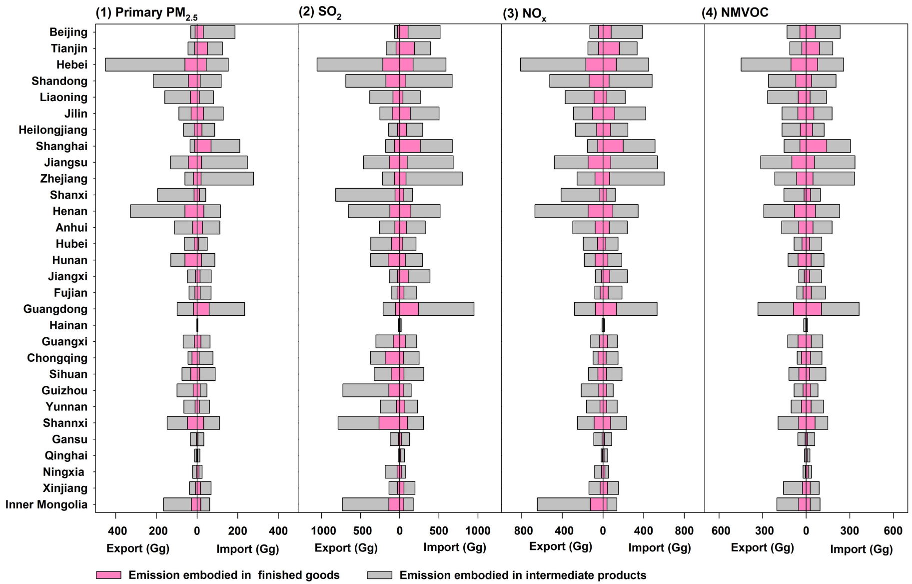

Figure 3. Balance of air pollutant emissions embodied in each province's interprovincial trade.

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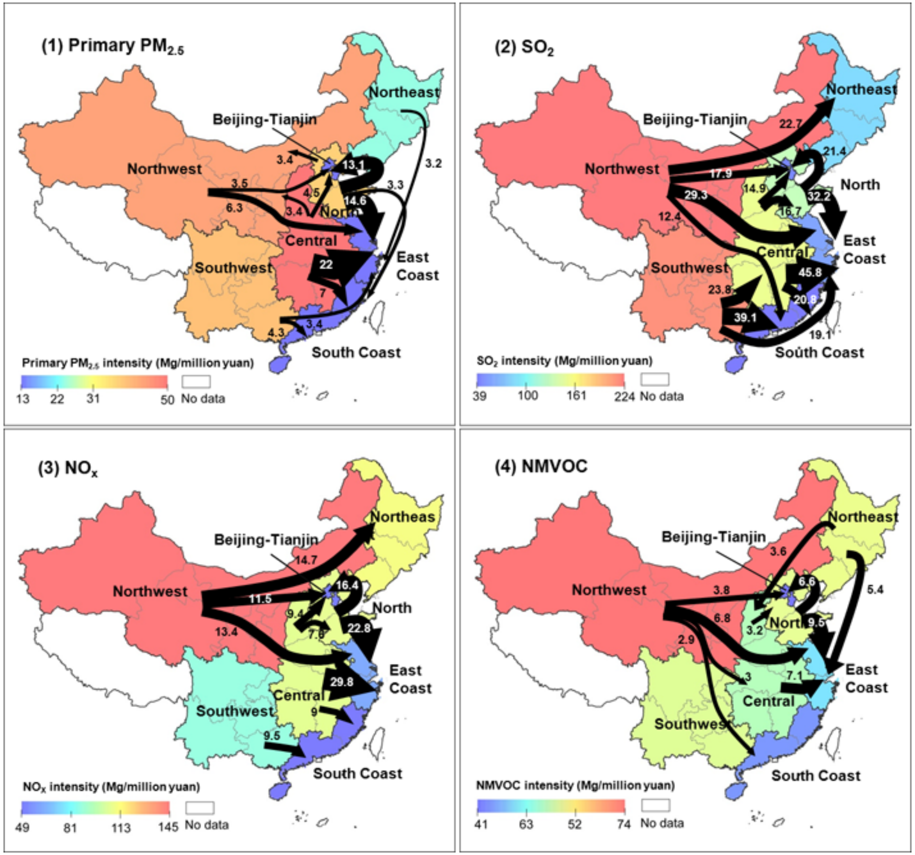

Figure 4. Largest net flows of primary $PM_{2.5}$, SO_2, NO_x, and NMVOC emissions embodied in interprovincial trade in 2007 (unit of flow: Gg). The shading in each region indicates the related production emission intensity.

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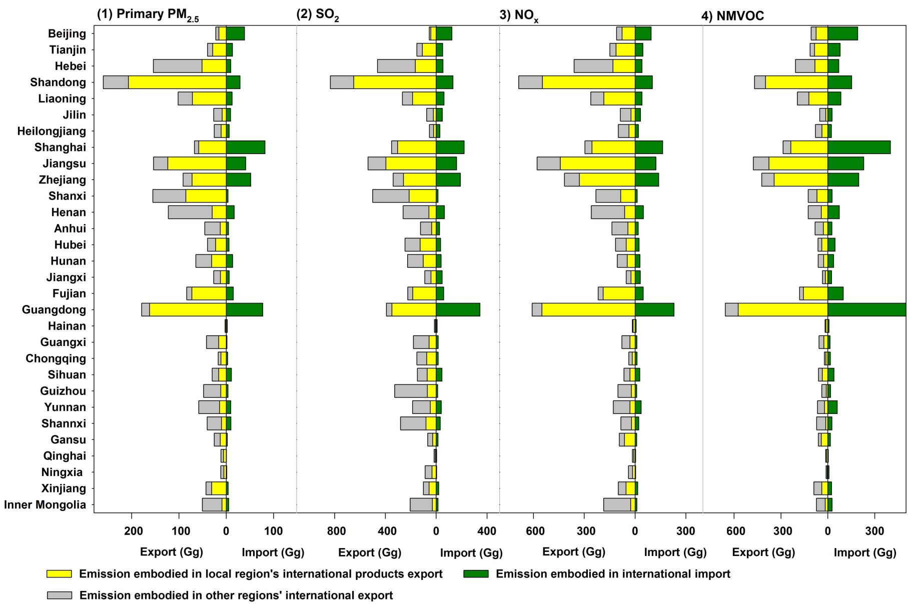

Figure 5. Balance of pollutant emissions embodied in each province's international trade.

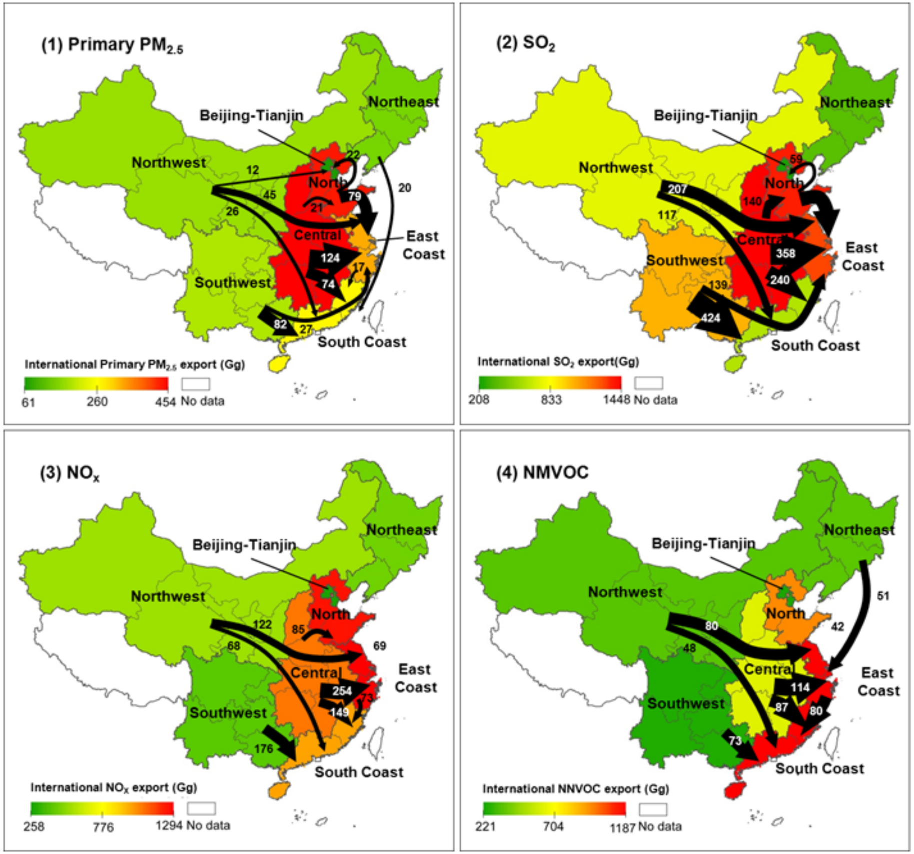

Figure 6. Regional pollutant emissions due to production of intermediate products to support other regions' international exports (unit of flow: Gg). The shading from green to red indicates each region's total international pollutant exports.

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