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The consumption-based black carbon emissions of China's megacities

Jing Meng[a], Zhifu Mi[b,c], Haozhe Yang[d], Yuli Shan[c], Dabo Guan[c1], Junfeng Liu[d]

[a] School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK

[b] Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China

[c] Tyndall Centre for Climate Change Research, School of International Development, University of East Anglia, Norwich NR4 7TJ, UK

[d] Laboratory for Earth Surface Processes, College of Urban and Environmental Sciences, Peking University, Beijing, People’s Republic of China

Highlights

- We calculate consumption-based black carbon emissions for four Chinese megacities.
- Capital formation is the largest contributor to consumption-based emissions.
- 44%-66% of consumption-based emissions are embodied in imports.
- Large net imported emissions are attributable to a relatively lower emission intensity.

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[1] Corresponding author：dabo.guan@uea.ac.uk

Abstract

A growing body of literature discusses the CO_2 emissions of cities. Still, little is known about black carbon (BC), a short-lived warming agent. Identifying the drivers of urban BC emissions is crucial for targeting cleanup efforts. A consumption-based approach enables all emissions to be allocated along the production chain to the product and place of final consumption, whereas a production approach attributes emissions to the place where goods and services are produced. In this study, we calculate the production-based and consumption-based emissions in 2012 in four Chinese megacities: Beijing, Shanghai, Tianjin and Chongqing. The results show that capital formation is the largest contributor, accounting for 37%-69% of consumption-based emissions. Approximately 44% of BC emissions related to goods consumed in Chongqing and more than 60% for Beijing, Shanghai and Tianjin occur outside of the city boundary. The large gap between consumption and production-based emissions can be attributed to the great difference in embodied emission intensities. Therefore, collaborative efforts to reduce emission intensity can be effective in mitigating climate change for megacities as either producers or consumers.

Keywords: Black carbon, megacities, input-output analysis, decomposition analysis

1 Introduction

Black carbon (BC) is mainly emitted by the incomplete combustion of fossil fuels and biofuel (Bond et al., 2013). BC is an efficient absorber of solar radiation and contributes to global climate change (Mitchell et al., 1997); its role is second only to CO_2 as the main driver of climate change (Bond et al., 2013; Ramanathan and Carmichael, 2008). Due to its short atmospheric lifetime, reducing BC emissions can immediately contribute towards the goal of limiting global warming to 2 °C above pre-industrial levels (Ramanathan and Carmichael, 2008; Rypdal et al., 2009; Shindell et al., 2012; Wallack and Ramanathan, 2009).

BC emissions are of concern at a variety of spatial scales ranging from the individual city to the globe (Bond et al., 2013; Cao et al., 2006; Jørgensen, 2016; Koch et al., 2009; Wang et al., 2012a). Asia contributes more than half of all global anthropogenic BC emissions, and China is the largest emitter, due to its rapid economic growth and urbanization (Wang et al., 2014a; Zhang et al., 2009). At present, more than half of China's population lives in urban areas (NBSC, 2015), and China's cities contribute more than 80% of the total energy consumption in China (Mi et al., 2016). Cities have been identified as having major potential for reducing energy consumption and related emissions (Chen and Chen, 2012, 2016a, b; Chen et al., 2015).

There are two widely used approaches to measuring urban emissions: production-based and consumption-based accounting. Production-based accounting is used to measure emissions caused by local production, without considering where goods are used or who ultimately uses them (Meng et al., 2016b; Wang et al., 2014a; Wang et al., 2014b; Wang et al., 2012a). These inventories have been extensively used to guide the implementation of emission control measures. By contrast, consumption-based accounting attributes all emissions occurring along the production chain to the final consumers of products (Davis and Caldeira, 2010; Meng et al., 2016c; Tukker and Dietzenbacher, 2013; Wiedmann, 2009). In this framework, emissions embodied in product imports are allocated to the city where they are consumed while the emissions embodied in exports are excluded (Peters, 2008). A series of studies have demonstrated that consumption-based accounting opens the door to new solutions to combating climate change that bring together producers and final consumers (Girod et al., 2014; Jakob et al., 2014; Steininger et al., 2015).

There are numerous studies on consumption-based greenhouse gas emissions for cities (Feng et al., 2014; Guo et al., 2012; Mi et al., 2015; Mi et al., 2016; Shao et al., 2016). Feng et al. (2014) analyzed consumption-based carbon emissions for four Chinese megacities and found that urban consumption imposed high emissions on surrounding regions via interregional trade. Mi et al. (2016) employed an input-output model to calculate consumption-based CO_2 emissions for thirteen Chinese cities and found that CO_2 emissions related to urban consumption are largely outsourced to other regions. Shao et al. (2016) also accounted for consumption-based carbon emissions from the fossil fuel consumption of Beijing in 2012. These studies all provided insights useful for designing climate mitigation policies as important complementary indicators to the production-based emission inventory. Some attention has also been paid to consumption-based air pollutant emissions in cities (Jiang et al., 2016; Li et al., 2016a).

However, few studies have focused on consumption-based BC emissions for cities. Li et al. (2016b) and Zhao et al. (2015a) all explored the emissions embodied in inter-provincial trade and international trade in 2007 and then derived the consumption-based emissions for 30 provinces in China, including Beijing, Tianjin, Shanghai and Chongqing. Meng et al. (2015a) assessed the consumption-based particulate matter emissions in Beijing and analyzed the impacts of domestic and international trade on Beijing's emissions. Hence, this study fills this gap by building consumption-based emission inventories for cities using the most recent data from 2012. We choose four megacities, Beijing, Tianjin, Shanghai and Chongqing, as our case study due to their prominent positions and data availability. The sources of BC emissions in this study consist of industrial emission sources (i.e. agriculture, industrial activity, power generation, transportation and non-transportation services) directly emitted from energy combustion and residential emissions (e.g. cooking and heating). To achieve our research targets, we first elaborate our methodology, including data collection and the detailed computation process. We then offer a detailed description of results and a deep analysis. We finally discuss policy implications for reducing BC emissions in our conclusions.

2 Methods

2.1 Estimation of production- and consumption-based BC emissions

Extended environmental input-output (EEIO) analysis is a popular tool that allows final consumption in one sector to be tracked to all other sectors (Miller and Blair, 2009). This method is being increasingly applied to analyze a wide-range of environmental issues such as greenhouse gas emissions (Guo et al., 2012; Shao et al., 2016), land use (Chen and Han, 2015; Costello et al., 2011), water consumption (Han et al., 2014; Zhao et al., 2015b), energy consumption (Li et al, 2016c; Yuan et al., 2010), air pollutants (Li et al., 2015; Meng et al., 2015a; Meng et al., 2015b), biodiversity loss (Lenzen, 2012), and materials use (Wiedmann et al., 2013).

In the framework of the original input-output analysis, the monetary balance of the urban economy is

$$X = Z + Y + E^{D} + E^{F} - M^{D} - M^{F} \tag{1}$$

where X is the vector of total economic output in each sector; Z represents the direct requirement coefficient matrix for each element; $z_{i,j}$ represents the required input from sector i to produce output in sector j; Y is a vector of domestic consumption, consisting of urban household consumption, rural household consumption, government expenditure, capital formation and inventory increase. E^D and E^F, respectively, represent the vectors of exports to other provinces and to other countries. M^D and M^F, respectively, represent the vectors of inflows from other provinces and imports from other countries.

Inflows M^D and Imports M^F represent final consumption and intermediate consumption. Due to the lack of an import matrix in the original IO table, we followed previous studies (Guan et al., 2009; Guan et al., 2014c; Lin et al., 2014; Meng et al., 2015a; Meng et al., 2015b; Weber et al., 2008) and assumed that all consumers (industry, government, and households) use inflows/imports in the same proportions. Thus, we used the following equations to split intermediate use (Z) and final use (F, including Y and E)

$$z_{ij}^D = z_{ij} \times (\mathrm{M}_i^D / (\mathrm{x}_i + \mathrm{M}_i^D + \mathrm{M}_i^F)) \tag{2}$$

$$z_{ij}^F = z_{ij} \times (\mathrm{M}_i^F / (\mathrm{x}_i + \mathrm{M}_i^D + \mathrm{M}_i^F)) \tag{3}$$

$$F_i^D = F_i \times (\mathrm{M}_j^D / (+ \mathrm{x}_i \quad \mathrm{M}_i^D + \quad \mathrm{M}_i^F \tag{4}$$

$$F_i^F = F_i \times (\mathrm{M}_i^F / (\mathrm{x}_i + \mathrm{M}_i^D + \mathrm{M}_i^F)) \tag{5}$$

Thus, equation (1) can be expressed as

$$\begin{aligned} X &= Z + Y + E^D + E^F - M^D - M^F \\ &= Z_{ij}^L + Z_{ij}^D + Z_{ij}^F + F_i^L + F_i^D + F_i^F - M_i^D - M_i^F \\ &= Z_{ij}^L + F_i^L + (Z_{ij}^D + F_i^D - M_i^D) + (Z_{ij}^F + F_i^F - M_i^F) \\ &= Z_{ij}^L + F_i^L \end{aligned} \tag{6}$$

Consumption-based emissions of an urban economy (*EC*) can be accounted by

$$EC = h(\mathrm{I} - A^D)^{-1} Y + \varepsilon^D M^D + \varepsilon^F M^F \tag{7}$$

Here, *I* is the identity matrix, A^D represents the normalized technology coefficients matrix or direct requirement coefficient matrix for each element; a_{ij} represents the required input from sector *i* (excluding inflows/imports) to produce unit output in sector *j*; $L=(I-A^D)^{-1}$ is the direct and indirect matrix, in which element L_{ij} represents how many products of sector *i* are locally needed to produce one unit of the product for final use in sector j. ε^D and ε^F are the embodied emissions intensity (direct and indirect emissions induced by unit final demand along the whole supply chain) of imported products from other regions domestically and imported products internationally, respectively. The embodied BC intensity of imported products can be found in Table A1 in supplementary information. Thus, $h(\mathrm{I}-A^D)^{-1}Y$ represents the emissions generated locally due to local final demand. $\varepsilon^D M^D$ and $\varepsilon^F M^F$ are the emissions embodied in domestic inflows and international imports, respectively.

Emissions embodied in exports can be expressed as:

$$EE = h(\mathrm{I}-A^D)^{-1}(E^{D\prime} + E^{F\prime}) \tag{8}$$

$E^{D}{}'$ and $E^{F}{}'$ are revised outflows/exports and remove the re-export of inflows/imports following equation (4) and (5).

2.2 Index decomposition analysis of emissions embodied in trade

The index decomposition of BC emissions embodied in trade is given by

$$E = \sum_i E_i = \sum_i Q \frac{Q_i}{Q} \frac{E_i}{Q_i} = \sum_i Q S_i F_i \tag{9}$$

where E describes the BC emissions embodied in exports or imports, Q is the GDP value of exports or imports, and S_i refers to the share of the GDP value for sector i, which reflects the economic structure. F_i is the BC emissions per unit of imported/exported finished products of sector i. Thus, the factor contributing to the net trade in embodied emissions can be expressed based on the logarithmic mean divisia index (LMDI) approach as:

$$\Delta E = E^{import} - E^{export} = \Delta E_Q + \Delta E_S + \Delta E_F \qquad (10)$$

where ΔE is the difference between the BC emissions embodied in imports (E^{import}) and the BC emissions embodied in exports (E^{export}); ΔE_Q, ΔE_S and ΔE_F refer to the effect of the trade volume of finished products, the trade structure and trade emissions intensity, respectively. ΔE_Q, ΔE_S and ΔE_F are expressed as:

$$\Delta E_Q = \sum_i w_i \ln(\frac{Q_i^t}{Q_i^o}) \qquad (11)$$

$$\Delta E_S = \sum_i w_i \ln(\frac{S_i^t}{S_i^o}) \qquad (12)$$

$$\Delta E_F = \sum_i w_i \ln(\frac{F_i^t}{F_i^o}) \qquad (13)$$

$$w_i = \frac{E_i^t - E_0^t}{\ln E_i^t - \ln E_0^t} \qquad (14)$$

Q_i^t, S_i^t and F_i^t are the trade volume, trade structure and emission intensity of imports, respectively. Q_i^0, S_i^0 and F_i^0 are the trade volume, trade structure and emission intensity of exports, respectively.

2.3 Data source

The energy-related BC emissions (C) was calculated by

$$C = \sum_{i=1}^{m} \sum_{j=1}^{n} E_{i,j} EF_{i,j} \qquad (15)$$

where C is total BC emissions (g); $E_{i,j}$ represents the energy consumption of fuel *j* in sector *i* (kg); $EF_{i,j}$ is the emission factor of energy j in sector *i* which incorporates the technology split and removal efficiency (Li et al., 2016b; Meng et al., 2015a; Meng et al., 2016b; Wang et al., 2012a; Wang et al., 2012b). The direct BC emission inventory covered all 30 economic sectors (Table A1) to adjust to the input-output table. Data regarding direct fossil energy in 2012 were from the China Emission Accounts and Datasets (CEADs, http://www.ceads.net/), which are all collected from the regional Statistical Yearbooks (Shan et al., 2016). Emission factors used in this study were obtained from previous studied (Wang et al., 2014a; Wang et al., 2012a; Wang et al., 2012b) , which had conducted an extensive literature reviewed to collect emission factor and built an emission factor database. Detailed methods to build the database and uncertainty analysis of the emission inventory can be found in previous studies (Meng et al., 2015a; Wang et al., 2012a; Wang et al., 2012b). A global BC emission inventory has also been compiled and is available online for free (http://inventory.pku.edu.cn/).

3 Results and Discussion

3.1 Production- and consumption-based BC emissions

Table 1 shows the socioeconomic information and BC emissions of the four megacities in 2012. We can see that Shanghai has the highest population density and the highest per capita territory BC emissions compared with the other three cities. Tertiary industries in Beijing and Shanghai contribute 76.4% and 60.4% to their GDP, respectively. By contrast, secondary industries are the economic engines in Tianjin and Chongqing. Tianjin has the highest per capita GDP and, at the same time, the highest consumption-based BC emissions per person. Chongqing is less developed than the other three cities, and its per capita GDP is less than half of the other three cities, while its per capita consumption-based emissions are approximately 70% of those in Beijing and Shanghai.

Insert Table 1

Insert Fig.1

The production-based BC emissions cover energy-related emissions from all industrial and residential households. The production-based BC emissions in Shanghai and Chongqing were 23.6 and 20.1 Gg, respectively, while Beijing’s and Tianjin’s production-based emissions were lower, at 11.9 and 13.9 Gg, respectively. Table A2 compares the BC emissions in this study with previous studies. The total emissions in the four megacities corresponds closely with the previous estimations, except that BC emissions in Beijing 2000 doubled the BC emissions in Beijing 2012 in this study. This can be attributed to the shift of 86-year-old Capital Iron and Steel Works, known as Shougang, from Beijing to Hebei since 2007.

An urban economy has extensive cross-boundary interactions in terms of monetary, commodity and resource flows (Jiang et al., 2016; Liu and Müller, 2013; Meng et al., 2015a; Shao et al., 2016). Territorial emissions in a city relate to local consumption and exports to other provinces or foreign regions, while the city also induced BC emissions outside of the city boundary. Figure 1 shows that more than 44% of BC emissions related to goods consumed in Chongqing and more than 60% for those consumed in Beijing, Shanghai and Tianjin occurred outside of the territorial city boundary in 2012. Overall, the consumption-based emissions in these four megacities were much larger than the production-based emissions, especially in Beijing and Tianjin, whose consumption-based emissions were almost double their production-based emissions. This finding of BC emissions in this study are similar to CO_2 emissions to some extent (Feng et al., 2014). The similar pattern for CO_2 and BC confirms that urban consumers in China's megacities are largely relying on goods produced elsewhere, thus inducing emissions and influencing the environment in other regions.

From a consumption perspective, these four megacities constitute various structures of final demand. More than half of the consumption-based emissions in Tianjin and Chongqing were induced by capital formation, e.g., road construction and housing development, in the cities. Capital formation requires a huge amount of steel, iron, and cement, as well as electricity, to support the production. These input materials are all highly emission-intensive products. The shares of emissions caused by capital formation in Beijing and Shanghai were slightly smaller (37% and 38%, respectively), while those for Tianjin and Chongqing were 69% and 48%, respectively. This high contribution of capital investments in the megacities to BC emissions is driven by rapid economic growth and urbanization, as well as being driven by government policies (Guo et al., 2012; Meng et al., 2015a; Mi et al., 2016; Shao et al., 2016). For megacities in 2007 (Feng et al., 2014), capital formation accounted for more than 50% of the total CO_2 consumption-based emissions. For BC emissions in 2012, Beijing and Shanghai had a relatively lower contribution of capital formation and a relatively higher contribution of urban household consumption compared to Tianjin and Chongqing, approaching those of developed western countries. As the capital city of China, Beijing has a relatively large contribution from government expenditure.

Urban household consumption was the second greatest contributor. Although the ratio of direct emissions from rural residential energy consumption to that from urban energy consumption ranged from 31% (Shanghai) up to a factor of 35 times (Chongqing), the level of embodied emissions in the commodities consumed by urban residents is much larger than that in the commodities consumed by rural residents, even amounting to 18 times in Shanghai, while the rural population and urban population were comparable. Annually, approximately 20 million people move from rural areas to urban areas, which incentivizes new infrastructure and housing requirements as well as substantial commodities purchases due to changing lifestyles (Feng and Hubacek, 2016). Household consumption is projected to drive growing BC emissions. The megacities are facing similar challenges in terms of BC emissions if they are to maintain their growth momentum. Therefore, consumer choices urgently need to be shifted, for example, energy-efficient dwellings, eating less (red) meat, lower fossil fueled mobility, and purchasing higher quality long-lived goods (Girod et al., 2013, 2014).

Insert Fig.2

3.2 Embodied BC emissions in trade

Emission inventories from a consumption perspective, rather than a production perspective, imply the need for policy instruments that allow the emissions of such key traded productions or services to be addressed. BC emissions embodied in imports and exports vary greatly in the four megacities (see Figure 3), but all four tend to import resources (e.g., coal, oil and gas) and materials produced by secondary industries. The sector of *mineral products* was the main contributor in all four megacities, ranging from 18% in Beijing to 23% in Chongqing. The sector of *coal, oil and gas* was the biggest contributor to Shanghai and Beijing's emissions embodied in imports, accounting for 19% and 37%, respectively. By contrast, emissions embodied in the *construction* sector were responsible for 49% of the total imported emissions in Tianjin. The monetary inflow in the *construction* sector has increased from 58 trillion in 2007 to 368 trillion in 2012 for Tianjin, at a growth rate of 44.7% annually (NBSC, 2014). The emissions embodied in exports in the four megacities are mainly related to the *transport and storage* sector, especially in Shanghai, which has 53% of emissions embodied in exports attributed to this sector. For all four cities, BC emissions embodied in imports were much greater than those embodied in exports. For example, the emissions embodied in Beijing's imports were four times the amount embodied in its exports.

Insert Fig.3

3.3 Socioeconomic driving forces of emissions imbalance

It can be seen that all four megacities were net importers of BC emissions and that imported and exported products differ greatly. These cities can be net importers of BC emissions for a number of reasons: (a) a relatively low emission intensity of GDP (i.e., the amount of direct and indirect BC emissions to produce a unit of GDP), (b) import specialization in carbon-intensive products, and (c) a trade deficit. The determinants are important research and policy issues. Because the international imports of these four cities were too small (less than 1%) compared to their domestic trade, we decomposed the net emissions embodied in domestic trade into the abovementioned three factors.

Insert Fig.4

Fig. 4 presents the contribution of each factor to the major difference in the net emissions transfer. Trade structure here reflects the percentage of emissions-intensive products within the traded products. The trade structure of Tianjin and Chongqing were responsible for approximately half of the net BC imports. What ultimately matters for Beijing and Shanghai is the difference in the intensity of inflows compared to outflows; emission intensity difference contributed 11.5 Gg and 7.6 Gg of the net BC emissions embodied in imports, which were partly offset by the trade deficit.

BC is an important component of fine particulate matter ($PM_{2.5}$) and has an adverse impact on human health and the environment (Bond et al., 2013). As part of the efforts to improve air quality, the Chinese government has imposed strict regulations on pollutant emissions in megacities (Meng et al., 2016a). One of these measures is to shift industry out of these regions without changing consumption patterns, which may result in an increase in total pollutant emissions. This increase would be due to generally inefficient production in less-regulated areas and geographically extended supply chains. A series of studies has highlighted that the emission intensity of developing country exports is much greater than that of developed country exports (Davis and Caldeira, 2010; Liu et al., 2016; Meng et al., 2016c); the same holds true for developing and developed cities within one country. Despite some policies such as installing scrubber, improving energy mix to reduce fossil fuel consumption (Hossain and Fara;

Rosen and Koohi-Fayegh, 2016), cost-effective mitigation of BC emissions may require policies that cover the entire supply chain, which in turn will depend upon a quantitative understanding of emissions transport between producers and consumers. Consumption-based accounting has clear benefits in terms of facilitating the diffusion of cleaner production practices and technologies to less developed regions (Guan et al., 2014a). For instance, the Clean Development Mechanism (CDM) concept is completely compatible with the consumption-based accounting of BC emissions. Peters (2008) posited that a consumption-based approach would allow project sponsors to enact mitigation projects in areas where they import products.

4 Conclusions

Consumption-based accounting has been widely used to open the door to new solutions to combating climate change. Compared to a production-based approach, a consumption-based method provides insight into the BC emissions in the production of products to support consumption. The aim of the consumption-based approach has not been to replace the production-based approach but rather to serve as a supplement. The policy implications include not only portions directed at reducing BC emissions in some specific industries, for instance, improving production technologies, but also options to alter consumption patterns.

In this study, we use the latest data to calculate the consumption-based BC emissions for four megacities in China and identify the forces driving the difference between consumption and production-based emissions. We find that consumption in these cities induces emissions not only locally but also beyond the boundary via interregional trade. For example, more than 60% of consumption-based BC emissions in Beijing and Shanghai were embodied in imports from other regions. However, the big gap in net emissions embodied in trade was not due to trade imbalances but instead stems from the large difference between the embodied emission intensity of exports from these megacities and imports from other regions. Indeed, this has already been demonstrated for CO_2 emissions (Feng et al., 2014; Mi et al., 2016). High levels of consumption in China's developed regions are driving emissions in less developed provinces, where CO_2 emission intensity is much greater. This finding highlights the magnitude and importance of interregional trade in transferring embodied emissions between regions. Improving technology and reducing carbon intensity are critical for mitigating climate change for megacities as either producers or consumers. The national government should coordinate design and implement effective mechanisms and channels to encourage technology transfer between the more and less developed regions of China (Guan et al., 2014b).

Capital formation was the largest contributor to consumption-based BC emissions in the four cities, particularly in Tianjin and Chongqing. Beijing and Shanghai were more like a mature economy, with a relatively lower contribution from capital formation and a relatively higher contribution from urban household consumption compared to Tianjin and Chongqing. For growing cities such as Tianjin and Chongqing, which are expanding their infrastructures, more sustainable urban forms and spatial planning are urgently needed as important long-term factors towards sustainable lifestyles (Creutzig et al., 2015; Feng and Hubacek, 2016; Ramaswami et al., 2016). Household consumption is the second largest driver, while the per capita BC footprint in urban areas was much larger than that in rural areas. In the future, more residents will transition from rural to urban lifestyles as China continues its rapid urbanization, leading to increased BC emissions related to household consumption. Clearly, improving emission intensity via production-focused efficiency measures and end-of-pipe control is essential. However, developing lifestyles that decouple economic growth and emissions will require substantial debates on the limits of green consumerism and the potential of sustainable consumption.

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Appendix. Supplementary material.

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