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Trend and driving forces of Beijing's black carbon emissions from sectoral perspectives

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ABSTRACT

Frequent occurrence of thick aerosol haze in Beijing attracts global attention. Based on recent epidemiological findings, black carbon (BC), an important haze component, the value of which is evaluated as an additional indicator of the adverse health effects of airborne particles, comparable to $PM_{2.5}$ (Particulate Matter with a diameter less than 2.5 μm). This study presents an unprecedentedly detailed sectoral BC emissions inventory of 2005–2012, and conducts what we believe to be the first logarithmic mean Divisia index (LMDI) analysis to identify socioeconomic drivers of BC emissions. It is found that although total energy use increased by 30%, BC emissions in Beijing decreased from 13.3 Gg in 2005 to 11.9 Gg in 2012, a 10% reduction over an 8-year period. Across all industry sectors, the leading emitters in 2005 included ferrous metals (1.6 Gg), non-metallic mineral products (1.2 Gg), and transportation (1.1 Gg), but were replaced by transportation (1.9 Gg), non-metallic mineral products (0.82 Gg) and construction (0.64 Gg) in 2012. As inferred by the LMDI analysis, changes in energy intensity, energy mix and industry structure potentially reduced BC emissions in Beijing during 2005–2012 by 6.3 Gg, 2.8 Gg and 1.1 Gg, respectively, while the growth of per capita GDP (Gross Domestic Product) and population tended to increase industrial BC emissions by 5.6 Gg and 2.6 Gg, respectively. This suggests that efforts toward improving energy and industry structures have reduced BC emissions by 32%. Therefore, further ameliorating the energy and industry structure in conjunction with further enhancing energy-use efficiency could be the most effective way to improve ambient air quality in Beijing.

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1. Introduction

With record levels of haze enveloping China's major cities, air pollution (especially fine particles less than 2.5 μm in diameter, known as $PM_{2.5}$) has provoked public concern (Chen et al., 2013; Lovett, 2013; Meng et al., 2015). In addition to impacts on ambient visibility and climate, $PM_{2.5}$ is responsible for a spike in the mortality rate of patients suffering from heart and lung diseases, owing to its small particle size (Cohen et al., 2005; Jacobson, 2007; Jansen et al., 2005). Epidemiological studies have shown that long-term exposure to high $PM_{2.5}$ concentrations is associated with increased mortality risk (Pop III et al., 2002, 2011; Schwartz et al., 2008). The new Chinese ambient air quality standards (GB 3095-2012, to be implemented in 2016 for all China) set annual $PM_{2.5}$ concentrations at 15 μg m^{-3} for Grade I (i.e., natural protection zones and other areas requiring special protection) and 35 μg m^{-3} for Grade II (residential, commercial, industrial and rural regions). This poses a substantial pressure to mitigate $PM_{2.5}$ relevant air pollution emissions, particularly in urban areas.

$PM_{2.5}$ is a heterogeneous mixture of sulfate, ammonium, nitrate, black carbon (BC), organic matter, and mineral dust. These components vary considerably depending on meteorological conditions and emission sources. The most recent evidence has shown that as an air quality indicator, $PM_{2.5}$ alone is insufficient for characterizing health risks of air pollution near combustion sources, e.g., motorized traffic on major roads (Janssen et al., 2011). Among all indicators, BC is deemed an additional air quality indicator in the evaluation of the health risks of air pollution that are dominated by primary combustion particles (Janssen et al., 2011). Moreover, in general the effects of BC on morbidity appear to be more robust

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than the effects of fine particles on morbidity (Geng et al., 2013; Wang et al., 2013a,b).

BC is a component of $PM_{2.5}$, emitted by incomplete combustion of fossil fuels, solid and outdoor biomass (Mayol-Bracero et al., 2002; Novakov et al., 2000; Wang et al., 2012a,b). According to the US Environmental Protection Agency (EPA, 2013), BC is associated with asthma, heart attacks, lung cancer and others. BC is also well known as a major contributor to global warming (Mitchell et al., 1997), second only to carbon dioxide (CO_2) (Bond et al., 2013; Ramanathan and Carmichael, 2008). Therefore, the mitigation of BC emissions are of great concern at a variety of spatial scales, from city to global (Bond et al., 2013; Cao et al., 2006; Koch et al., 2009; Wang et al., 2012a,b).

With population growth and substantial fossil and biofuel consumption, BC emissions in China have dramatically increased, from 341 Gg/yr (1949) to 1957 Gg/yr (2007) (Wang et al., 2012a,b), and now is the largest contributor (one-fourth) to global anthropogenic BC emissions (Bond et al., 2004; Zhang et al., 2009a,b). Cities in China is responsible for 75% of total energy consumption in China (Dhakal, 2010; Li and Chen, 2013; Li et al., 2013), and contribute substantial energy-related BC emissions. Under the ongoing trend of urbanization in China, it is projected that additional 350 million people will migrate to urban regions and demand more energy consumption (Fung, 2013). This will potentially impose huge threat on the environment and human health by releasing more air pollution emissions (e.g., BC). Therefore, regarding the large energy consumption and population density, cities are the key areas for controlling energy related BC emissions in China.

Beijing, the capital city of China, has frequently experienced severe air pollution episodes during the past few years (Chen et al., 2013; Lovett, 2013). In particular, BC concentration in Beijing is about 10 times that of other industrialized cities (e.g., New York) (Qin et al., 2006; Sun et al., 2004). Combustion of coke, raw coal, and noncommercial biomass was estimated to be the main contributor to municipal BC emissions in Beijing in 2000 (Liu and Shao, 2007; Qin and Xie, 2011; Streets et al., 2001; Wang et al., 2012a,b, 2014). To offer more targeted and effective recommendations for mitigation strategies, a comprehensive analysis of energy-related BC emissions in Beijing, particularly with detailed sectoral information, is indispensably needed.

Aiming to analyze the trend and driving forces of Beijing's BC emissions and identify the most emission-intensive industry, this study builds a BC emission inventory with high sectoral resolution (including 55 economic sectors and household consumption) during 2005–2012, and then conducts the first (to our knowledge) logarithmic mean Divisia index (LMDI) analysis to explore the socioeconomic drivers (e.g., energy mix, industrial structure, energy intensity, etc.) of BC emissions in Beijing.

2. Methodology and data sources

2.1. Fossil fuel-related BC emission inventory

Given the availability of data, the emission inventory was begun in 2005. Data on Beijing's energy usage were collected from Beijing Statistical Yearbooks (BSY, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013) and the China Statistical Yearbooks (2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013). Fuel types included coal, coke, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas (LPG) and natural gas. Abbreviations and sector information of the 55 economic sectors and household consumption are shown in Table 1.

BC emissions attributable to energy consumption are determined by:

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

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 (g/kg), denoting the mass of BC emitted per unit fuel consumed or product manufactured.

Owing to a lack of local measurements of the BC emission factor (EF_{BC}), many EF_{BC} measurements in previous emission inventories were converted from the product of the emission factor of PM (EF_{PM}) and BC/PM ratios ($F_{fine} \times F_{BC}$) (Bond et al., 2004; Streets et al., 2001). Here, F_{fine} represents submicron particulates of total emissions and F_{BC} is the BC fraction of the submicron particles. To assign the appropriate emissions to each type of combustion, an extensive literature review of emissions factors was undertaken to compile the EF_{BC} database used in this work (Cooke et al., 1999; Cooke and Wilson, 1996; Penner et al., 1993; Qin and Xie, 2011; Streets et al., 2001; Wang et al., 2012a,b). This study followed earlier studies (Wang et al., 2012b, 2014) and assumed that the previously reported EF_{BC} values follow a lognormal distribution. Log-transformed mean and standard deviation scores were calculated from BC emission factors reported in the literature. Table 2 lists EF_{BC} of four categories, which were further assigned to the 55 economic sectors when belonging to the same broad category. Emission factors in some sectors can change over time because of varying uses of combustion and control technologies. Since this study covers only 8 years, it is assumed that no fundamental change in EF_{BC} during such a short period, as previous study did (Liu and Shao, 2007).

2.2. Decomposition analysis

Decomposition analysis (DA) methods have been widely used to explore socioeconomic drivers of environmental pressures (Hoekstra and Van Den Bergh, 2002). Two decomposition approaches are by far the most popular, namely, structural decomposition analysis (SDA) and index decomposition analysis (IDA). SDA is based on input–output coefficients and final demands from input–output tables, whereas IDA is more suitable for time-series analysis using data with sufficient temporal and sectoral detail (Hoekstra and Van den Bergh, 2003; Zhang et al., 2009a,b). The advantage of the IDA approach is that it can be easily applied to any data at any level of aggregation (Ma and Stern, 2008). The various indexing methods in IDA are summarized in Table 3 (Ang, 2004; Granel, 2004).

Based on Table 3, LMDI analysis is regarded as preferable to other decomposition methods, with advantages of path independency, consistency in aggregation, and ability to handle zero values (Ang, 2004; Ang et al., 1998; Ang and Liu, 2001). Many studies have used LMDI to identify driving forces of energy consumption (Ma and Stern, 2008; Ou et al., 2007; Zhang and Guo, 2013) and carbon emission changes (Liu et al., 2007; Kang et al., 2014; Wang et al., 2013a,b). These studies concluded that LMDI analysis can provide important policy insights.

LMDI analysis compares a set of indices between the base and final year of a given period, and explores the accumulated effects of these indices on the trend of emissions over that period (Ma and

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