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Black carbon emissions from trucks and trains in the Midwestern and Northeastern United States from 1977 to 2007

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HIGHLIGHTS

- BC emissions from trucks and rail have decreased between 1977 and 2007.
- These decreases are noted despite large growth in the volume of freight shipped.
- Regulatory efforts to decrease BC emissions from trucks has been largely successful.
- Historically the fabricated metal industrial sector has dominated BC emissions.
- However, clustering of transportation results in smaller decreases in urban centers.

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ABSTRACT

We have developed a framework to estimate BC emissions from heavy-duty diesel trucks and trains engaged in transporting freight in the Midwestern and Northeastern United States (MNUS) from 1977 to 2007. We first expand on a previous development of a regional econometric input–output model (REIM) that has been used to estimate commodity flows between 13 states in the MNUS (plus the rest of the US) and 13 industrial sectors. These commodity flow data are then distributed over the MNUS using a stylized link-and-node network, which creates great circle transportation links between nodes in each state at the county with the largest population. Freight flows are converted to BC transportation emissions and the resulting BC emissions are compared to the MACCity BC emissions inventory. We find that from 1977 to 2007 potential emission growth from the continued increase in freight tonnage in the MWUS is counteracted by decreases in the BC emission factor of heavy-duty diesel trucks, which results in an overall decrease of BC emissions by 2007. One sector (fabricated metal product manufacturing) has dominated the BC transportation emissions throughout 1977 to 2007 with transportation emissions remaining relatively unchanged from 1977 to 1997 and then decreasing out to 2007. The BC transportation emissions are concentrated in and around the urban centers, which serve as transportation and production nodes for industrial manufacturing. Our BC emissions are distributed along stylized transportation corridors that are not well represented in emissions inventories that largely distribute emissions via a population proxy. The framework established in this study can be used to estimate future BC transportation emissions under a set of stylized economic, technological, and regulatory scenarios.

1. Introduction

Black Carbon (BC) aerosols influence both air quality and the global climate; they are a human health hazard (e.g. Janssen et al., 2012) with a net radiative forcing on the order of 1 W m^{-2} of which nearly one-third is attributed to fossil fuel combustion (Bond et al., 2013). In industrialized nations, including the US where biomass combustion (i.e. cooking and heating stoves) emissions are relatively low, on-road heavy duty diesel vehicles (HDDVs) in the transportation sector are the dominant source of BC emissions

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(Bond et al., 2013). The transportation sector in the US has transformed dramatically since the 1970s: freight volumes have nearly tripled, increasing at a rate that is faster than the growth of US Gross National Product (GNP) (US DOT, 2013); emission factors for BC from HDDVs, which account for over 50% of US BC transportation emissions (US EPA, 2012a), have declined by nearly 80% (US EPA, 2012a; US EPA, 2012b); and the transportation sector has transformed as a part of an increasingly interconnected global economy that is dependent on just-in-time deliveries of both intermediate and finished commodities (Donaghy, 2012).

The ultimate impact of an increased demand for transportation and a concurrent decrease in BC emission factors on the total BC emissions is complicated. This paper examines the factors by which freight flows impact BC emissions in the Midwestern and Northeastern US (MNUS) over a historical period (1977–2007) in order to determine and describe the major factors that impact the overall trend. We use a regional econometric input–output model (REIM) to derive time series on commodity flows in value terms, which we convert to freight flows in weight terms. Then, distributing the derived freight flows by mode of transport in a stylized transportation network, and employing available historical emission factors for HDDV and rail, we estimate gridded BC emissions. Our methodology allows us to isolate the BC emissions that result from the individual influences of economic and regulatory forces. This framework provides us with the capability to examine future BC emissions under a variety of economic and regulatory scenarios.

There have been many factors influencing BC emissions from freight transportation in the MNUS from 1977 to 2007. The majority of BC emissions from the transportation sector come from the HDDV fleet with a minor contribution from the rail fleet (ICF, 2005). The transportation of freight by HDDVs and rail is controlled by demand from producers and consumers of finished and semi-finished products, which themselves are driven by underlying dynamics of both regional and global economies including growth, supply and demand, and globalization. At the same time, particulate matter (PM) emissions, including BC emissions, have been subject to increasingly stringent regulatory efforts from the US EPA (US EPA, 2012a) and from local and regional municipalities (e.g. NYSDEC, 2014).

From 1977 to 2007 the value of all freight movement in the US has grown at an annual rate of roughly 5%, which is more than twice as fast as the growth of the country's Gross National Product (GNP) (US DOT, 2013). Much of the increase in demand for freight shipment is the result of aggregated economic growth as well as changes in the structure, connectivity, and infrastructure of industrial producers, which is often referred to as the geography of production (e.g. Feenstra, 1998; Donaghy, 2007). In addition, the transportation sector has experienced advancements in information technologies, which has increased the efficiency and reliability of the freight transportation sector. This has resulted in a transition to “just-in-time” inventory management systems where products and materials can be shipped quickly in an “on-demand” basis (e.g. Krishnamarthy, 2007) with a growing trend towards regular shipments of unfinished goods between production centers throughout the production process (Castells, 2000). Subsequently the industrial production process has grown more dependent upon the transportation sector. Essentially, industries have taken advantage of regional economies of scale (Feenstra, 1998) and economies of scope (Jones and Kierzkowski, 2001), which has resulted in a “hollowing out” (or a reduction of local purchasing by firms) and “clustering” (or agglomeration of similar types of activities) of production and transportation nodes (Munroe et al., 2007) as industries move their production processes to locations that maximize advantages from economies of scale. This results in, for instance, factories and production centers that may have been previously distributed throughout the region to gather in and around the most efficient transportation nodes (i.e. urban centers). An example is the regular transportation of unfinished automobile parts between Canada and the US (Anderson and Coates, 2010), where car parts experience multiple border crossings throughout the production process (Anderson, 2012). This is a significant change from the traditional vertically integrated or traditional assembly line production process (Feenstra, 1998).

At the same time, the US EPA and regional municipalities have become increasingly aware of the negative health effects of BC emissions (e.g. Anenberg et al., 2012) and have indirectly promulgated increasingly stringent controls on BC by continuously tightening the National Ambient Air Quality Standard (NAAQS) for all particulate matter (PM) (US EPA, 2012a, 2012b, 2013). This regulatory tightening, combined with a continued increase in technological efficiencies in transportation technologies, has resulted in the HDDV emission factor for BC to drop from 1.29 μg/g of fuel in 1977 to 0.39 μg/g in 2007 (from the US EPA MOVES software, US EPA, 2012b). This downward trend in BC emission standards is expected to continue into the future. Data on the emission factor of BC from the private rail industry are limited.

This study examines the connection between regional BC emissions and regional economic activities through model representations of the individual behavior of sectors within the MNUS. The MNUS has a large population clustered in urban centers with high manufacturing and transportation volumes among a small enough number of states to keep the computational intensity at reasonable levels. This regional focus also allows for a more complete representation of the regional activities that other inventories with global spatial coverage are often unable to capture. Instead of distributing emissions based on a population proxy, as is common practice in a number of standard emission inventories (e.g. Bond et al., 2004, 2007; Lamarque et al., 2010) we distribute emissions based on an stylized transportation network that allows us to examine sub-regional impacts of the transportation sector on BC air quality. We compare our methodology to other existing BC emissions inventories and explore the strengths and weaknesses of our derived BC emissions. The framework created through the development of the REIM and in this work allows for the direct estimation of future BC emissions under a variety of economic, technological, and regulatory scenarios through changes in transportation patterns and emission factors.

We attempt in this paper to answer two primary questions: (1) What has the BC emissions trend been from HDDV and rail transportation sources between 1977 and 2007 and what are the major factors that have driven that trend? (2) What economic sectors dominate these BC emissions and what major changes have occurred from 1977 to 2007? Our analysis focuses primarily on the overall processes driving spatial and temporal BC emissions over the historical period. Section 2 describes the methodology of this study, including details of the derivation of the necessary commodity-flow data, their conversion to freight-flow data, and the process by which they are distributed by mode and transport network, and the format and caveats of the resultant BC emissions. Section 3 evaluates these BC emissions against an existing BC emission inventory. Section 4 explores the implications of these BC emissions including the interaction between increasing freight volume and decreasing emission factors, the major contributing sectors and their trends, and the regional impact of BC emissions in the Midwestern and Northeastern US.

2. Methods

In this section we detail the process and steps taken to estimate a time series of gridded BC emissions from both HDDV and rail