Environmental Pollution 214 (2016) 86–93

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Quantifying sources of elemental carbon over the Guanzhong Basin of China: A consistent network of measurements and WRF-Chem modeling☆

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ARTICLE INFO

Article history:
Received 5 January 2016
Received in revised form
27 February 2016
Accepted 18 March 2016

Keywords:
Elemental carbon
Source apportionment
WRF-Chem
The Guanzhong Basin

ABSTRACT

We conducted a year-long WRF-Chem (Weather Research and Forecasting Chemical) model simulation of elemental carbon (EC) aerosol and compared the modeling results to the surface EC measurements in the Guanzhong (GZ) Basin of China. The main goals of this study were to quantify the individual contributions of different EC sources to EC pollution, and to find the major cause of the EC pollution in this region. The EC measurements were simultaneously conducted at 10 urban, rural, and background sites over the GZ Basin from May 2013 to April 2014, and provided a good base against which to evaluate model simulation. The model evaluation showed that the calculated annual mean EC concentration was 5.1 μgC m^{-3}, which was consistent with the observed value of 5.3 μgC m^{-3}. Moreover, the model result also reproduced the magnitude of measured EC in all seasons (regression slope = 0.98–1.03), as well as the spatial and temporal variations (r = 0.55–0.78). We conducted several sensitivity studies to quantify the individual contributions of EC sources to EC pollution. The sensitivity simulations showed that the local and outside sources contributed about 60% and 40% to the annual mean EC concentration, respectively, implying that local sources were the major EC pollution contributors in the GZ Basin. Among the local sources, residential sources contributed the most, followed by industry and transportation sources. A further analysis suggested that a 50% reduction of industry or transportation emissions only caused a 6% decrease in the annual mean EC concentration, while a 50% reduction of residential emissions reduced the winter surface EC concentration by up to 25%. In respect to the serious air pollution problems (including EC pollution) in the GZ Basin, our findings can provide an insightful view on local air pollution control strategies.

1. Introduction

In recent years, China has exhibited severe air pollution in the form of fine particulate matter ($PM_{2.5}$) (Chan and Yao, 2008; Cao, 2014). Elemental carbon aerosol (EC), alternatively referred to as black carbon aerosol (BC) (Petzold et al., 2013), is an important component of $PM_{2.5}$, especially in the Guanzhong (GZ) Basin which is the most EC-polluted area in Western China (Cao et al., 2005, 2007, 2012a; Shen et al., 2011; Wang et al., 2015; Zhao et al., 2015a, b). EC is emitted directly from the incomplete combustion of fossil fuels (e.g. coal and diesel) and biomass (e.g. biofuel, agricultural and forest fires) (Cao et al., 2006; Zhang et al., 2009). EC considerably influences climate change by heating the atmosphere and cooling the land surface through its absorption of solar

☆ This paper has been recommended for acceptance by Kimberly Jill Hageman.
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http://dx.doi.org/10.1016/j.envpol.2016.03.046
0269-7491/

radiation (Jacobson, 2001; Ramanathan et al., 2001; Chung and Seinfeld, 2005; Ramanathan and Carmichael, 2008). EC also has adverse effects on air quality resulting from its contribution to regional haze and poor visibility (Cao et al., 2012b; Zhang et al., 2015a). Furthermore, EC has deleterious impacts on human health because of absorbing harmful gases, such as polycyclic aromatic hydrocarbons (PAHs) (Dachs and Eisenreich, 2000; Anenberg et al., 2011, 2012).

Many efforts have been made to estimate EC emissions in China (Streets et al., 2003a, b; Bond et al., 2004; Zhang et al., 2009; Lei et al., 2011; Lu et al., 2011; Kondo et al., 2011; Qin and Xie, 2012; Fu et al., 2012; Li et al., 2015). The annual mean Chinese EC emission estimated by previous studies for the year 2000–2010 varied from 1.0 to 2.9 TgC yr^{-1}, with strong regional and seasonal variations of the source proportion. For example, the major emission source of EC in large parts of China is residential sectors. This is particularly true in the winter in Northern China (residential sources contribute more than 60% to total EC emissions), a time and place in which home heating abound (Zhang et al., 2009; Li et al., 2015). However, when turning to the Yangtze River Delta region in Eastern China, we find the emissions from industries dominate in the spring, summer and autumn (~50%, Zhang et al., 2009; Li et al., 2015). In the Pearl River Delta region in Southern China, the transportation sectors play the most important roles (65%, Zheng et al., 2012).

Chemical transport models bridge the relations between the emission sources and ambient concentrations. However, we find limited studies on model-based characterizations of source contributions to EC pollutions (Chen et al., 2013; Liu et al., 2014; Kumar et al., 2015; Zhang et al., 2015b; Zhao et al., 2015a). Kumar et al. (2015) used WRF-Chem to simulate surface black carbon (BC) aerosol over the Bay of Bengal and Arabian Sea. They suggested that residential sources were the major anthropogenic sources (61%) of BC concentration in South Asia and that regional-scale transport contributed up to 25% in Western and Eastern India. Zhang et al. (2015b) used the CAM5 model to calculate the BC concentrations from various regions and sectors over the Himalayas and Tibetan Plateau. They pointed out that the largest contribution to the annual mean BC concentration in the Himalayas and Tibetan Plateau is from biofuel and biomass emissions from South Asia, followed by fossil fuel emissions from South Asia. Also focusing on the GZ Basin, Zhao et al. (2015a) used WRF-Chem to characterize fate of BC emitted from local and various neighboring areas. They found that the local and regional transport sources, respectively, contributed 60 and 40% to the annual mean BC concentration. They further pointed out that the regional transport was mostly from east of the GZ Basin (65%), but the sectorial contribution of the local GZ sources were not quantified.

In this study, we conducted a year-long simulation of EC concentrations in the GZ Basin. The simulation was driven by current best bottom-up estimate of EC emissions in this area. We compared the calculated results with the surface EC measurements in a network of 10 sites over the GZ Basin. The goals of the study were to analyze the temporal and spatial characteristics of EC pollution and then to identify the region- and sector-specific source contributions in the GZ Basin. This assessment result is expected to provide useful information for potential mitigation actions.

2. Model and data

2.1. The WRF-Chem model

The regional chemical model WRF-Chem (Weather Research and Forecasting Chemical model, version 3.2) was applied to simulate the EC distributions in the GZ Basin. The WRF model is a fully compressible, Euler non-hydrostatic model that simulates meteorological fields. Based upon WRF, the WRF-Chem model includes an online calculation of dynamical inputs (e.g., winds, temperature, boundary layer and clouds), transport (advection, convective and diffusive), dry and wet depositions, gas phase chemistry, as well as radiation and photolysis rates (Tie et al., 2003). A detailed description of WRF-Chem has been given by Grell et al. (2005), and some modifications in the chemical scheme have been introduced by Tie et al. (2007). The Yonsei University (YSU) PBL scheme is used in the model. This scheme uses counter-gradient terms to represent fluxes and explicitly considers the entrainment effect to calculate the PBL heights (Hong et al., 2006; Noh et al., 2001). Dry deposition is calculated as per Wesely (1989), with EC deposition velocity being 0.001 m s^{-1}. The Lin microphysics scheme (Lin et al., 1983), the Noah land-surface model (Chen and Dudhia, 2001), the longwave radiation parameterization (Mlawer et al., 1997) and the shortwave radiation parameterization (Dudhia, 1989) were used in this study.

The simulation domain (Fig. S1) centered on the GZ Basin, a region in China developing quickly but with high pollution levels (Shen et al., 2009, 2011; Wang et al., 2015). The GZ Basin, surrounded by the Qinling Mountains and the Loess Plateau, has a population of 22.4 million people. It is located in Western China and belongs to the mainland monsoon climate. We applied a study domain with a 3 × 3 km horizontal resolution and a 28-layer vertical structure. NCEP FNL Operational Global Analysis data provided the initial and boundary conditions for the meteorological fields. The initial and boundary conditions of EC were taken from monthly mean outputs from a global chemical transport model (Model for Ozone and Related chemical Tracers, MOZART) (Tie et al., 2005; Emmons et al., 2010). The initial EC was 1.5 μg m^{-3} as averaged for simulation domain, and the annual-mean boundary EC was 1.3 μg m^{-3} as averaged for the four laterals. The simulation was conducted for a period of one year, from May 2013 to April 2014. Considering the computational costs, we simplified the WRF-Chem model by reducing the complex chemical schemes of gases and aerosols. Only the modules related to the simulation of EC (emission, transport, and deposition) were kept (Zhao et al., 2015a, b).

2.2. Emissions

As a starting point for this study, we compiled the current best bottom-up EC emission inventories in the GZ Basin and the surrounding areas. These inventories included EC emissions from anthropogenic and open biomass burning sources. Table 1 summarizes the annual EC emission for the GZ Basin used in this study.

The anthropogenic EC emission was obtained from the Multi-resolution Emission Inventory for China (Li et al., 2015) for the year 2009, and included industry, power generation, transportation, as well as residential sources. Zhao et al. (2015a) applied this emission inventory to WRF-Chem and extensively compared

Table 1
EC emission estimates in the GZ Basin.

Source sector	Emission (GgC y^{-1})
Anthropogenic[a]	28.5 (98%)
Industry	7.9 (27%)
Power generation	<0.1 (<1%)
Residential sources	13.9 (48%)
Transportation	6.7 (23%)
Open Biomass Burning[b]	0.5 (2%)
Total	29.0 (100%)

[a] From Multi-resolution Emission Inventory for China (MEIC) for the GZ Basin.
[b] From Fire Inventory from NCAR (FINN) for the GZ Basin.