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Temporal trends and spatial variation characteristics of primary air pollutants emissions from coal-fired industrial boilers in Beijing, China☆

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A B S T R A C T

Coal-fired combustion is recognized as a significant anthropogenic source of atmospheric compounds in Beijing, causing heavy air pollution events and associated deterioration in visibility. Obtaining an accurate understanding of the temporal trends and spatial variation characteristics of emissions from coal-fired industrial combustion is essential for predicting air quality changes and evaluating the effectiveness of current control measures. In this study, an integrated emission inventory of primary air pollutants emitted from coal-fired industrial boilers in Beijing is developed for the period of 2007–2013 using a technology-based approach. Future emission trends are projected through 2030 based on current energy-related and emission control policies. Our analysis shows that there is a general downward trend in primary air pollutants emissions because of the implementation of stricter local emission standards and the promotion by the Beijing municipal government of converting from coal-fired industrial boilers to gas-fired boilers. However, the ratio of coal consumed by industrial boilers to total coal consumption has been increasing, raising concerns about the further improvement of air quality in Beijing. Our estimates indicate that the total emissions of PM_{10}, $PM_{2.5}$, SO_2, NO_x, CO and VOCs from coal-fired industrial boilers in Beijing in 2013 are approximately 19,242 t, 13,345 t, 26,615 t, 22,965 t, 63,779 t and 1406 t, respectively. Under the current environmental policies and relevant energy savings and emission control plans, it may be possible to reduce NO_x and other air pollutant emissions by 94% and 90% by 2030, respectively, if advanced flue gas purification technologies are implemented and coal is replaced with natural gas in the majority of existing boilers.

1. Introduction

Coal is an important fuel for industrial manufacturing sector and daily residential use in China (Chen et al., 2015; Tian et al., 2012; Zhao et al., 2010). However, coal combustion process produces and emits many types of hazardous air pollutants (HAPs), such as primary particulate matter (PM), BC, OC, SO_2, NO_x, CO, VOCs and various heavy metals (Hu et al., 2013; Tian et al., 2010, 2015). Furthermore, these pollutants undergo a series of chemical and physical reactions in the atmosphere, producing secondary fine PM that contributes to deterioration in regional air quality and visibility and poses considerable risks to human health (Guo et al., 2012; Jathar et al., 2013; Lei et al., 2011a).

Several studies (Li et al., 2015; Yu et al., 2013; Zhang et al., 2013) have indicated that coal consumption is an important contributor

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to energy production and is regarded as one of the most important sources of PM and SO_2. According to the official $PM_{2.5}$ source appointment results published by the Beijing Environmental Protection Bureau (BJEPB), coal combustion accounted for 22.4% of the total mass concentration of $PM_{2.5}$ in 2013 (BJEPB, 2014). Huang et al. used the MM_5-CAM_X-PAST model system for source attribution and determined that coal combustion and industrial sector contributed approximately 66.1% of the total SO_2 concentration (Huang et al., 2012). The large amount of coal combustion in China has raised concerns about its considerable adverse impacts on both regional- and global-scale air quality (Shen et al., 2010; Willey et al., 2015; Zhang et al., 2015).

Because of the continuous growth of the economy and population in Beijing (Sun et al., 2010; Zhao et al., 2013), there has been a rapid increase in energy consumption, with an annual average growth rate of approximately 5% since 2007. To control coal combustion emissions and prevent severe $PM_{2.5}$ and haze pollution, local authorities in Beijing have implemented a series of integrated air pollution control measures, such as banning the construction of new coal combustion projects, shutting down existing coal-fired power plants and replacing coal-fired boilers with gas-fired boilers for heating and industrial production. Despite these measures, the total amount of coal consumed in Beijing has not dropped substantially from 2007 (2985 tons) to 2013 (2099 tons) (NBSC, 2014). The reduction in coal use has come primarily from coal-fired power plants, which already have advanced air pollution control devices installed to reduce the release of PM, SO_2 and NO_x, whereas the coal burned by industrial boilers has remained nearly unchanged. Coal consumption by industrial coal-fired boilers has increased from 30.7% of total coal consumption in 2007 to 37.2% in 2013. Compared with coal-fired power boilers, coal-fired industrial boilers emit more gaseous pollutants (SO_2, NO_x, CO, VOCs, etc.) and PM. These additional emissions, which are caused by the application of different combustion facility patterns and relatively poor control measures, often contain more toxic components, such as heavy metals (Hg, As, Pb, etc.), PAHs and their derivatives.

Recently, several studies have been conducted to estimate emissions from industrial coal-fired boilers in Beijing (Lang et al., 2012; Su et al., 2011; Wang et al., 2015a; Zhao et al., 2012; Zhou et al., 2014, 2015). However, due to a lack of detailed source-specific information, previous estimates were primarily made using general statistical data. The emissions were mostly calculated from large-area sources and then geographically distributed according to GDP, land use, or population indexes, resulting in a rather high uncertainty in the emission inventory and low accuracy regarding source positions and associated HAPs emissions.

The purpose of this study is to improve upon the existing work described above by developing a unit-based emission inventory for coal-fired industrial boilers using a bottom-up methodology. We analyzed the historical trends of coal-fired industrial boilers in Beijing from 2007 to 2013, calculated the typical HAPs emissions using detailed source-specific information regarding combustion boiler types and flue gas purification technology, and projected the future emissions from coal-fired industrial boilers till 2030.

2. Data and methods

2.1. Study domain

Beijing, the capital city of P. R. China, is located at 39°56′N, 116°20′E on the northwestern edge of the North China Plain. It is surrounded by the Taihang and Yanshan Mountains to the west, north, and northeast (Gao et al., 2014). The city covers 16,410.54 km^2, is divided into 16 prefecture districts and is inhabited by approximately 211,480,000 residents (BMBS, 2014). The demands for energy in the industrial sector and for residential heating are fairly high.

2.2. Methodology

Annual emissions of various HAPs from each boiler are calculated seriatim using boiler-specific coal consumption and best available emission factors (BJMEMC, 2005; SEPA, 2008) for the applied control technologies, which were determined based on field measurements and investigation. The integrated emission inventory developed here includes four types of gaseous air pollutants (SO_2, NO_x, CO and VOCs) and PM in two size ranges: $PM_{2.5}$ (particulates with diameters less than 2.5 μm) and PM_{10} (particulates with diameters less than 10 μm). The algorithm for a bottom-up emission inventory of primary air pollutants from coal-fired industrial boilers can be expressed using the following equations:

$$E_{SO_2} = \sum_i 2 \times M_{i,m} \times Sar_i \times \left(1 - \eta_{i,m}\right) \tag{1}$$

$$E_{NO_x/PM_y} = \sum_i \sum_j \sum_k \left(M_{i,j,k,l,m} \times EF_{NO_x/PM_y,i,j,k,l,m} \times \left(1 - \eta_{l,m}\right)\right) \tag{2}$$

$$E_{CO/VOCs} = \sum_i \sum_j \sum_k \left(M_{i,j,k} \times EF_{CO/VOCs,i,j,k}\right) \tag{3}$$

where the subscripts *i,j,k,l,m,y* represent the boiler unit, boiler type, installed capacity, starting year, emission control technology applied and PM size fraction, respectively; *EF* is the assumed average emission factor for each pollutant; *M* is the volume of annual coal combustion; *Sar* is the average sulfur content of feed coal; and η is the assumed average removal efficiency of control technologies for various pollutants.

2.3. Activity data

Activity data is obtained by conducting field investigations organized by BJEPB and cross-checked for coincidence and a comprehensive analysis of annual statistics (BJEPB, 2014; BMBS, 2014). A database of coal-fired industrial boilers is compiled at the unit level. We collect and use detailed point source information from 2599 coal-fired industrial enterprises or institutions (totally 4964 coal-fired industrial boilers). The detailed information includes the latitude and longitude of each boiler, boiler type, installed capacity, starting year, annual coal consumption for each unit, installed emission control technologies, and starting time of the technologies. The geographical locations of the 2599 coal-fired industrial enterprises or institutions are illustrated in Fig. 1. In Beijing, coal-fired industrial boilers are primarily used for heating in winter, this application accounts for nearly 68% of all coal-fired industrial boiler use in terms of the number of boilers and 80% in terms of total installed capacity. Because of the adjustments to industrial structure in the past years, the Beijing government has shut down many highly polluting enterprises; the use of coal-fired industrial boilers for industrial production has been reduced, accounting for 32% in terms of total number and 20% in terms of total capacity.

As seen in Fig. 2, the amount of coal used by industrial boilers has not decreased obviously during the past years, whereas the reduction of coal consumption in other sectors has been much higher than that in the industrial sector, leading to an increase in the proportion of coal consumed by industrial coal-fired boilers relative to the total coal consumption in Beijing (BMBS, 2014).