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Benefits of China's efforts in gaseous pollutant control indicated by the bottom-up emissions and satellite observations 2000–2014

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HIGHLIGHTS

- The trends in emissions and VCDs match well in China except for SO_2.
- The recent controls prove more effective than those in earlier years except for CO.
- Coal consumption dominated the growth of NO_X emissions and NO_2 VCDs till 2012.
- The effects of air pollution controls differed by region and species in the country.
- Varied emissions from specific sources are evaluated through satellite observation.

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ABSTRACT

To evaluate the effectiveness of national air pollution control policies, the emissions of SO_2, NO_X, CO and CO_2 in China are estimated using bottom-up methods for the most recent 15-year period (2000–2014). Vertical column densities (VCDs) from satellite observations are used to test the temporal and spatial patterns of emissions and to explore the ambient levels of gaseous pollutants across the country. The inter-annual trends in emissions and VCDs match well except for SO_2. Such comparison is improved with an optimistic assumption in emission estimation that the emission standards for given industrial sources issued after 2010 have been fully enforced. Underestimation of emission abatement and enhanced atmospheric oxidization likely contribute to the discrepancy between SO_2 emissions and VCDs. As suggested by VCDs and emissions estimated under the assumption of full implementation of emission standards, the control of SO_2 in the 12th Five-Year Plan period (12th FYP, 2011–2015) is estimated to be more effective than that in the 11th FYP period (2006–2010), attributed to improved use of flue gas desulfurization in the power sector and implementation of new emission standards in key industrial sources. The opposite was true for CO, as energy efficiency improved more significantly from 2005 to 2010 due to closures of small industrial plants. Iron & steel production is estimated to have had particularly strong influence on temporal and spatial patterns of CO. In contrast to fast growth before 2011 driven by increased coal consumption and limited controls, NO_X emissions decreased from 2011 to 2014 due to the penetration of selective catalytic/non-catalytic reduction systems in the power sector. This led to reduced NO_2 VCDs, particularly in relatively highly polluted areas such as the eastern China and Pearl River Delta regions. In developed areas, transportation is playing an increasingly important role in air pollution, as suggested by the increased ratio of NO_2 to SO_2 VCDs. For air quality in mega cities, the inter-annual trends in emissions and VCDs indicate that surrounding areas are more influential in NO_2 level for Beijing than those for Shanghai.

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1. Introduction

Due to tremendous growth of the economy and fossil fuel

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consumption, China has been suffering from severe air pollution for decades (Zhang et al., 2012). Based on satellite observations and chemical transport simulations, the highest of tropospheric NO_2 in the world have been indicated in eastern China, the region with the largest densities of population and economic activity in the country (Richter et al., 2005). Existing emission inventories indicate that China is the dominant source of gaseous pollutants including SO_2, NO_X and CO in Asia (Streets et al., 2003; Zhang et al., 2009; Cofala et al., 2007; Kurokawa et al., 2013).

Facing the big challenge of improving air quality, China undertook a series of measures to improve energy efficiency and to reduce emissions during the 11th Five-Year Plan (11th FYP) period (2006–2010). Small industrial boilers and kilns with low energy efficiency were gradually shut down or replaced with larger ones featuring advanced dust collectors. Installation of flue gas desulfurization (FGD) systems has been required for all new thermal power units since 2005. At the same time, the fraction of washed coal has increased from 33% in 2005 to 51% in 2010 (Wang and Hao, 2012). These measures are thought to have been effective: national emissions of SO_2 and particulate matter (PM) were officially reported to decline by 14% and 30% from 2005 to 2010, respectively (MEP, 2011). Other studies with more conservative assumptions have likewise suggested substantial benefits of emission controls, particularly for SO_2 and CO (Lu et al., 2011; Zhao et al., 2012a, 2013).

The measures in 11th FYP, however, failed to restrain the growth of NO_X emissions that are critical to formation of $PM_{2.5}$ and O_3 in the atmosphere (Zhao et al., 2013). Big challenges on air quality improvement still existed over the country (Wang and Hao, 2012). During the 12th FYP period (2011–2015), China aimed to reduce the annual emissions of SO_2 and NO_X by 8% and 10% compared to 2010, respectively. More stringent measures were taken to control NO_X emissions, including the use of selective catalytic/non-catalytic reduction (SCR/SNCR) systems in the power sector and staged implementation of tighter emission standards on vehicles. Moreover, a series of new standards with aggressive emission limits for power, cement, and the iron & steel industries have been issued successfully since 2011. Those measures are believed to have helped achieve national targets of emission abatement, but their impacts on emissions and air quality have been seldom quantified.

In this study, the emissions of gaseous pollutants in China are estimated using bottom-up methods for the most recent 15 years (2000–2014), in order to examine the effectiveness of national air pollution control policies, particularly for the years after 2010. Vertical column densities (VCDs) from satellite observation are used to evaluate inter-annual trends and the spatial distribution of emissions, and temporal and spatial patterns of ambient levels of gaseous pollutants across the country. By combining the information of emissions and satellite observations, the impacts of controls on given source types are analyzed, and the source contributions to air quality for two developed mega cities and their surrounding regions are further identified.

2. Data and methods

2.1. Emission inventory

China's annual emissions of SO_2, NO_X, CO and CO_2 are estimated from 2000 to 2014 using bottom-up methods described in previous studies (Zhao et al., 2011, 2012a, 2012b, 2013). Anthropogenic emission sources include four main categories: thermal power plants (TPP, including both electricity generation and heat production), all other industry (IND), transportation (TRA, including on-road and non-road subcategories), and the residential & commercial sector (RES, including fossil fuel and biomass combustion subcategories). IND is further divided into cement production (CEM), iron & steel plants (ISP), other industrial boilers (OIB), and other non-combustion processes (PRO), reflecting the structure of available data. In general, the annual emissions of each species are calculated by province using Eq. (1) and are then aggregated to national level:

$$E_{i,j,t} = \sum_{k}\sum_{m}\sum_{n} AL_{j,k,m,n,t} \times EF_{i,j,k,m,t} \times R_{i,j,k,m,t} \times \left(1 - \eta_{i,n,t}\right) \quad (1)$$

where i, j, k, m, n and t stand for species, province, sector, fuel type, emission control technology, and year, respectively; AL is the activity level, either energy consumption or industrial/agricultural production; EF is the unabated emission factor; R is the penetration rate of the relevant emission control technology; and η is the removal efficiency of that technology.

The activity levels are compiled mainly from Chinese official energy (NBS, 2013a, 2014) and industrial economic statistics (NBS, 2013b, 2014), as discussed in our previous work (Zhao et al., 2013). Detailed data on energy budgets by province for 2013 and 2014 were unavailable at the time of writing and thus the national fast-track statistics for these two years had to be used to extrapolate provincial activity levels by applying consistent provincial shares with 2012.

Emission factors, expressed as the pollutant emissions per unit of activity, have changed significantly during the study period, particularly for power, transportation, and certain industrial sectors including cement and iron & steel production, as a series of successive air pollution control measures have been implemented. In this work, two cases, “primary” (PRI) and “standard” (STD), are developed to represent the inter-annual trends in emission factors and thereby emissions. Following the method in our previous work (Zhao et al., 2013), PRI case analyzes the penetrations of advanced combustors with improved energy efficiency and air pollutant control devices (APCDs) with improved pollutant removal efficiency. As shown in Fig. S1 in the supplement, the increased use of advanced combustors and APCDs is assumed to have led to continuously reduced emission factors for most emission sources and pollutant species, with a few exceptions such as NO_X from cement kilns (Lei et al., 2011) and from heavy-duty vehicles (Yao et al., 2011; Wu et al., 2012). In addition to PRI case, STD case is developed to re-estimate the SO_2 and NO_X emissions for 2011–2014 (i.e., there is no difference between the two cases for SO_2 and NO_X emissions for 2000–2010 and for other species for 2000–2014). This case optimistically assumes that the series of emission standards for power and industrial sectors issued or updated since 2011 (listed in Table S1 in the supplement) have been strictly enforced. All of the tightened emission limits and schedules of implementation are assumed to be met, for both existing and new emission sources (Zhao et al., 2014). Based on the emission limits from the standards, emission factors from the power, cement, iron & steel and non ferrous metal smelting industries are estimated to have declined further in STD compared to those in the PRI case, as summarized in Table S2 in the supplement.

2.2. Satellite data

Satellite observations can provide information on temporal trends and spatial patterns of atmospheric chemistry composition and concentrations of pollutants of concern. In this work, the VCDs of NO_2, SO_2, and CO from various satellite retrieval products are used to evaluate the anthropogenic emissions and the effects of pollution control policies.

The Ozone Monitoring Instrument (OMI) aboard the EOS Aura

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