Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-374
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 2 May 2018

Atmospheric Chemistry and Physics Discussions
Open Access
EGU

Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions

Bo Zheng[1,†], Dan Tong[2], Meng Li[2], Fei Liu[1], Chaopeng Hong[2], Guannan Geng[2], Haiyan Li[1], Xin Li[2], Liqun Peng[1], Ji Qi[1], Liu Yan[2], Yuxuan Zhang[2], Hongyan Zhao[2], Yixuan Zheng[2], Kebin He[1,2], and Qiang Zhang[2]

[1]State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, People's Republic of China
[2]Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University, Beijing, China
[†] Present address: Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ, UMR8212, Gif-sur-Yvette, France

Correspondence to: Qiang Zhang (qiangzhang@tsinghua.edu.cn)

Abstract. To tackle the problem of severe air pollution, China has implemented active clean air policies in recent years. As a consequence, the emissions of major air pollutants have decreased and the air quality has substantially improved. Here, we quantified China's anthropogenic emission trends from 2010–2017 and identified the major driving forces of these trends by using a combination of bottom-up emission inventory and Index Decomposition Analysis (IDA) approaches. The relative change rates of China's anthropogenic emissions during 2010–2017 are estimated as follows: −62% for SO_2, −17% for NO_x, +11% for NMVOC, +1% for NH_3, −27% for CO, −38% for PM_{10}, −35% for $PM_{2.5}$, −27% for BC, −35% for OC, and +18% for CO_2. The IDA results suggest that emission control measures are the main drivers of this reduction, in which the pollution controls on power plants and industries are the most effective mitigation measures. The emission reduction rates markedly accelerated after the year 2013, confirming the effectiveness of China's Clean Air Action that was implemented in 2013. We estimated that during 2013–2017, China's anthropogenic emissions decreased by 59% for SO_2, 21% for NO_x, 23% for CO, 36% for PM_{10}, 33% for $PM_{2.5}$, 28% for BC, and 32% for OC. NMVOC emissions increased by 11% and NH_3 emissions remained stable from 2010–2017, representing the absence of effective mitigation measures for NMVOC and NH_3 in current policies. The relative contributions of different sectors to emissions have significantly changed after several years' implementation of clean air policies, indicating that it is paramount to introduce new policies to enable further emission reductions in the future.

1 Introduction

China produces the most air pollution in the world and contributes 18–35% of global air pollutant emissions (Hoesly et al., 2018). The major air pollutants China emits the most include sulfur dioxide (SO_2), nitrogen oxides (NO_X), carbon monoxide

(CO), nonmethane volatile organic compounds (NMVOC), ammonia (NH_3), and particulate matter (PM), including black carbon (BC) and organic carbon (OC). These pollutants constitute the majority of the precursors of $PM_{2.5}$ and O_3 pollution as well as those of short-lived climate forcers, which exert harmful effects on human health, agriculture, and ecosystems. These pollutants not only represent local to regional environmental problems but are also a global problem due to global warming issues. To tackle the problems of both air pollution and climate change, it is important to fully understand the trends and drivers of Chinese emissions.

The years since 2010 have been an extraordinary period for China in the fight against air pollution. For the first time, China has added the index of $PM_{2.5}$ into its air quality standards, with an annual upper mean limit of 35 μg m^{-3} (Zhang et al., 2012). In 2013, the annual average concentrations of $PM_{2.5}$ were 106 μg m^{-3}, 67 μg m^{-3}, and 47 μg m^{-3} in Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Pearl River Delta, respectively; these concentrations are all worse than China's 35 μg m^{-3} standard and two to five times higher than the WHO's acceptable standards. To attain this air quality standard, China has strengthened its emission standards to achieve reductions in air pollutant emissions. These upgraded emission standards and the timeline for their implementation have accelerated since 2013, when the Action Plan on the Prevention and Control of Air Pollution (denoted as the Clean Air Action) was implemented (China State Council, 2013). The three metropolitan regions mentioned above were required to reduce their concentrations of $PM_{2.5}$ by 15–25% by the year 2017 compared with their 2013 levels, and all other provinces in China were required to reduce their PM_{10} concentrations by 10%. These air quality targets have imposed more stringent clean air requirements since 2013 and finally reduced $PM_{2.5}$ concentrations by 28–40% from 2013–2017 (China, 2018). Space- and ground-based observations have confirmed the improvement of China's air quality (Krotkov et al., 2016; Liu et al., 2016; Zhang et al., 2017; Zhao et al., 2017; Zheng et al., 2018).

Establishing linkages between air quality improvements and mitigation efforts requires the use of the most recent emission inventory. However, there are no official data about how much air pollutants are emitted by China every year. The inventories developed by researchers often lag several years behind the present, leaving China without up-to-date emission inventories. Currently, there are no emission datasets that cover the period of 2010–2017. To understand the progress in air cleaning, we are in urgent need of China's most recent emission inventories, which will benefit both scientific studies and policy-making. Given that China accounts for approximately one-third of global emissions, these data will also facilitate a better understanding of the latest trends in global emissions.

In this paper, we analyze the key trends and drivers of China's anthropogenic emissions from 2010–2017. During this period, China announced unprecedented measures to improve air quality. The purpose of this study is to summarize what China has done in recent years and to evaluate how these actions have influenced anthropogenic emission trends. We first provide a comprehensive overview of China's clean air actions since 2010, especially the stringent measures that took effect after 2013 (Sect. 2). Then, we use a bottom-up method (Sect. 3) to estimate the 2010–2017 trend in Chinese emissions (Sect. 4.1) shaped by these mitigation measures. The driving factors are analyzed at the national and sectoral levels using the approach of Index Decomposition Analysis (Sect. 4.2). We separate the influence of pollution control from the influence of economic growth on the emission trend. Finally, the emission trends are evaluated against space- and ground-based observations of SO_2 and NO_2, as well as the top-down constraints inferred from these observations (Sect. 4.3). Concluding remarks are given in Sect. 5.

2 China's clean air actions

The clean air policies that have been implemented by China since 2010 are summarized in Fig. 1. These mitigation measures cover all the major source sectors and have become increasingly stringent over time. Before 2013, strengthening the emission standards for power and industrial sectors was the key pollution control measure. For example, the emission limits of coal-fired power plants were 400 mg m^{-3} for SO_2, 450–1100 mg m^{-3} for NO_x, and 50 mg m^{-3} for particulates before 2012 (the standard GB 13223-2003). After 2012, all new and existing coal-fired plants were required to achieve new limit values of SO_2, NO_x and particulates of 100 (200 for existing units), 100 and 30 mg m^{-3} (the standard GB 13223-2011), respectively. China also set new emission standards for the flat glass industry and the iron and steel industry before 2013. Because other industries (e.g., the cement industry and industrial boilers) lacked stringent emission standards, they still used outdated legislation on emission limits implemented approximately ten years ago during the period of 2010–2013.

China committed to reducing $PM_{2.5}$ pollution in 2013 for the first time ever. To fulfill the air quality target, the government developed eight pollution control measures that were more stringent and ambitious than ever before. With these new measures, the emission limits set by existing standards were further tightened, and more stringent emission source controls were adopted not only to reduce emissions but also to improve energy efficiency and promote a structural change in energy use patterns. We briefly describe the eight measures implemented during 2013–2017 in the following section.

1) "Ultralow" emission standard for power plants. Strengthening emission standards is key in the pollution control of coal-fired power plants. With the 2012 emission standard enacted and fully met, China pledged in December 2015 to further reduce emissions from coal power by 60% by 2020 using the "ultralow emission" technique. The emission limits for SO_2, NO_x and particulates are 35, 50 and 10 mg m^{-3}, respectively, which means that emissions from coal-fired plants must be brought to the level of those from gas-fired plants. Of the current power plants, 71% operated close to "ultralow emission" levels in 2017 (China, 2018).

2) Phase out outdated industrial capacity. Small and inefficient factories that cannot meet efficiency, environment, and safety standards have been eliminated in recent years. As a result, the average energy intensity, or energy consumed per unit of industrial gross output, steadily decreased for steel (−3.3%), cement (−2.9%), aluminum (−1.0%), ethylene (−4.2%), and synthetic ammonia (−3.0%) from 2013–2016 (National Bureau of Statistics, 2018a). The average efficiency of coal-fired power units, or grams of coal equivalent consumed per kilowatt-hour of power supply, improved from 321 gce kWh^{-1} to 309 gce kWh^{-1} from 2013–2017 (National Bureau of Statistics, 2018a; National Energy Administration, 2018).

3) Strengthen industrial emission standards. Since 2013, all industrial emission standards have been strengthened; limits have been tightened and the targeted emission sources and air pollutants have been expanded. Figure 1 summarizes all the national emission standards specific to air pollutants, and there are another 22 comprehensive standards that specify the

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-374
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 2 May 2018

maximum amounts of waste materials in gas and water for different industries. These standards, including both new and upgraded ones from previous levels, have covered all the emission-intensive industries in China.

4) Phase out small and polluted factories. The tightened emission standards have driven industries to upgrade and adopt cleaner technologies. Small and polluted factories that cannot meet emission standards are being retired and replaced with larger facilities. Large industrial plants that have the potential to improve their overall performance by upgrading are required to meet the latest emission legislation as early as possible. These plants must operate close to or better than the original design performance and install end-of-pipe pollution control devices to reduce emissions.

5) Install NMVOC emission control facilities. The petrochemical industry has been required to implement the Leak Detection and Repair (LDAR) program and cut NMVOC emissions by 30% by 2017. In addition, a wide range of solvent-using activities also increase NMVOC emissions. Solvents appear in many industrial processes, such as dissolving substances, providing media for chemical reactions, and acting as a dispersion medium for coatings. High solids and waterborne paints contain much fewer organic chemicals, and powder coatings and liquid coatings are both solvent-free. The substitution of these new solvents and coating techniques represents the latest requirement of China's emission standards.

6) Eliminate small coal-fired industrial boilers. China shut down all coal boilers with capacities of smaller than 7 MW in urban areas by the end of 2017 and cleaned all existing and new large boilers with SO_2 and particulate control technologies. The elimination of small coal-fired boilers in suburban and rural areas is still in progress.

7) Replace residential coal use with electricity and natural gas. Direct coal-burning in the residential sector is being replaced with natural gas and electricity to tackle air pollution in the countryside (China, 2018). China is striving to switch to electricity and gas-powered heating from coal in millions of residences in North China. To facilitate this fuel switch, northern Chinese provinces have cut nonpeak household power prices to reduce the cost of electricity heating, and new gas heating systems are being built in suburban and rural regions. These policies can reduce coal use in the residential sector.

8) Strengthen vehicle emissions standards, retire old vehicles, and improve fuel quality. Tightened emission standards have also driven automakers to adopt cleaner technologies. Fuel economy standards have allowed automakers to reduce the amount of fuel use by new cars from 8.0 L 100 km^{-1} in 2010 to 6.9 L 100 km^{-1} in 2015, and the 2020 target is 5.0 L 100 km^{-1} (China State Council, 2016). The latest Euro 5/V emission standards were implemented in 2017, and newly registered vehicles must comply with these stringent emission standards. Additionally, all "yellow label" vehicles were eliminated by the end of 2017. "Yellow label" vehicles refer to gasoline and diesel vehicles that fail to meet Euro 1 and Euro III standards, respectively.

3 Methods and Data

3.1 Bottom-up emission inventory

Here, we use the framework of the MEIC (Multi-resolution Emission Inventory for China, http://www.meicmodel.org) to estimate China's anthropogenic emissions from 2010–2017. MEIC is a bottom-up emission inventory model which covers

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31 provinces in mainland China and includes ~700 anthropogenic sources. Emissions for each source in each province are estimated as follows:

$$Emis_{i,j,k} = A_{i,j} \times \sum_{m} \left(X_{i,j,m} \times EF_{i,j,k,m} \times \sum_{n} \left(C_{i,j,m,n} \times \left(1-\eta_{k,n}\right)\right)\right) \quad (1)$$

where i represents the province, j represents the emission source, k represents the air pollutants or CO_2, m represents the technologies for manufacturing, n represents the technologies for air pollution control, A is the activity rate, X is the fraction of a specific manufacturing technology, EF is the unabated emission factor, C is the penetration of a specific pollution control technology, and η is the removal efficiency. The details of the technology-based approach and source classifications can be found in Zhang et al. (2007, 2009), Lei et al. (2011), and Li et al. (2017b).

The underlying data in MEIC model are gathered from different sources. Activity rates of energy consumptions by fuel type, by sector, and by province are derived from Chinese Energy Statistics (National Bureau of Statistics, 2018a, 2018b; National Energy Administration, 2018). Productions of various industrial products and penetration of different technologies are collected from a wide variety of statistics (for details, please refer to Lu et al., 2010, Lei et al. 2011). We also use unpublished data from the Ministry of Environmental Protection to supplement the technology penetration data which are absent in statistics, specifically for penetration rates of different emission control technologies (Qi et al., 2017, Zheng et al., 2017). Detailed activity rates by province for the year 2017 are not available when the emission trends presented in this work were developed. In this case, we used national activity data for the year 2017 (National Bureau of Statistics, 2018b; National Energy Administration, 2018) and downscaled these national total data to each province using the weighting factors from 2016 data at provincial level. Unabated emission factors in MEIC are compiled from a wide range of previous studies, for instance, SO_2 from Lu et al. (2010), NO_x from Zhang et al. (2007), NMVOC from Li et al. (2014), CO from Streets et al. (2006), primary aerosols (PM_{10}, $PM_{2.5}$, BC, and OC) from Lei et al. (2011), and CO_2 from Liu et al. (2015). We then override those data by local emission factors summarized in Li et al. (2017c) wherever available, to represent the most recent progress on emission factor developments in China.

Emissions from power plants are estimated following the unit-based approach developed by Liu et al. (2015). In summary, we track the emissions of each unit from electricity generation, fuel quality, and the progress in emission control using unit-specific parameters. Emissions from on-road vehicles are estimated using a county-level emission model developed by Zheng et al. (2014), which resolves the spatial-temporal variability of vehicle ownership, fleet turnover (i.e., new technology penetration), and emission factors. Detailed documentation of the method and data for power plants and on-road vehicles can be found in Liu et al. (2015) and Zheng et al. (2014), respectively.

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3.2 Index Decomposition Analysis

We use Index Decomposition Analysis (IDA) to study the driving forces of China's anthropogenic emissions from 2010–2017. IDA is one of the major techniques used to analyze the impact of changes in indicators on emission trends (Hoekstra and van den Bergh, 2003). The IDA method is described as follows:

Eq. (1) can be converted to a matrix form using the following formula:

$$Emis_{i,j,k} = A_{i,j}\mathbf{x}\mathbf{E}\boldsymbol{\eta} \quad (2)$$

The technology distribution factors $X_{i,j,m}$ in Eq. (1) are assembled into the row vector **x**, and the relevant unabated emission factors $EF_{i,j,k,m}$ are assembled into a diagonal matrix **E**. The column vector $\boldsymbol{\eta}$ represents the average removal efficiencies weighted by the penetration rates $C_{i,j,m,n}$ of all types of pollution control technologies. According to Eq. (2), over a given period of time, any changes in emissions can be decomposed into their component driving factors using Eq. (3).

$$\Delta Emis_{i,j,k} = \Delta A_{i,j}\mathbf{x}\mathbf{E}\boldsymbol{\eta} + A_{i,j}\Delta\mathbf{x}\mathbf{E}\boldsymbol{\eta} + A_{i,j}\mathbf{x}\Delta\mathbf{E}\boldsymbol{\eta} + A_{i,j}\mathbf{x}\mathbf{E}\Delta\boldsymbol{\eta} \quad (3)$$

where Δ is the difference operator. The four multiplicative terms in Eq. (2) are converted into four additive terms in Eq. (3). Each additive term represents the contribution of one driving factor to the changes in emissions, while all other factors are kept constant. For example, $\Delta\boldsymbol{\eta}$ is the change in pollutant removal efficiencies, and the last term in Eq. (3) represents the change in total emissions caused by end-of-pipe abatement measures, with the activity range $A_{i,j}$, technology distribution **x**, and unabated emission factor **E** assumed to be constant.

Technically, the decomposition with four factors in Eq. (3) has 4! = 24 unique first-order decomposition results. In this study, we use the average of all possible first-order decompositions (Dietzenbacher and Los, 1998) in the analysis of emission drivers. By way of illustration, one of the 24 possible decompositions is shown in Eq. (4).

$$\begin{aligned}\Delta Emis_{i,j,k} &= Emis_{i,j,k}(t_1) - Emis_{i,j,k}(t_0)\\ &= \Delta A_{i,j}\mathbf{x}(t_1)\mathbf{E}(t_1)\boldsymbol{\eta}(t_1) + A_{i,j}(t_0)\Delta\mathbf{x}\mathbf{E}(t_1)\boldsymbol{\eta}(t_1)\\ &\quad + A_{i,j}(t_0)\mathbf{x}(t_0)\Delta\mathbf{E}\boldsymbol{\eta}(t_1) + A_{i,j}(t_0)\mathbf{x}(t_0)\mathbf{E}(t_0)\Delta\boldsymbol{\eta}\end{aligned} \quad (4)$$

The decomposition analysis generates a four-dimensional array with dimensions that represent the year (2010–2017), province (size=31), emission source (size>700), and emission drivers (i.e., A, **x**, **E**, and $\boldsymbol{\eta}$ in Eq. (2)). This means that for each pollutant, the year-to-year change in emissions can be attributed to the drivers of A, **x**, **E**, and $\boldsymbol{\eta}$ by source and by province. A is the activity effect (e.g., fuel combustion), and the other three factors constitute the overall effect of air pollution control. This study is mainly concerned with source contributions rather than province contributions; hence, we sum the 4-D array of the decomposition analysis results along the province dimension and perform the following analysis at the country scale.

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3.3 Satellite-based and *in situ* observations

We adopt atmospheric observations to evaluate and validate the emission trends estimated in this study. We use NO_2 column retrievals from the DOMINO V2 product (Boersma et al., 2011) and SO_2 column retrievals from the OMI V3 product (Krotkov et al., 2015). The 2010–2017 trends of satellite observations are calculated over East China, where anthropogenic sources are dominant relative to natural sources and are compared against the emission trends of NO_x and SO_2, respectively. Several recent papers have used satellite retrievals to infer recent trends in emissions from East Asia or China. These results are summarized in this study and compared to our emission estimates. We also collect surface-level SO_2 and NO_2 concentration data from national air quality monitoring stations (http://106.37.208.233:20035/) for the period of 2013–2017. These real-time monitoring stations were established in 2013 and had the ability to report hourly concentrations of criteria pollutants from over 1400 sites in 2017.

4 Results and discussion

4.1 Emission trends

Since 2010, China's anthropogenic emissions have decreased by 62% for SO_2, 17% for NO_x, 27% for CO, 38% for PM_{10}, 35% for $PM_{2.5}$, 27% for BC, and 35% for OC (Table 1). Most of these emission reductions have been achieved since 2013, when the Clean Air Action was enacted and implemented. SO_2 and NO_x are the only air pollutants that were incorporated into national economic and social development plans with emission reduction targets in China. The 12th Five-Year Plan required the total national emissions of SO_2 and NO_x to be cut by 8% and 10% from 2011–2015, respectively, while the actual reductions were much larger than planned due to the stringent pollution control requirements implemented after 2013. During this period, CO emissions decreased by 23%, whereas CO_2 emissions increased by 2%, reflecting China's improved combustion efficiency and emission control. The years since 2013 also observed a sharp drop in particulate emissions, in contrast with the flattening emissions observed before 2013. This trend is more evident for coarse particles because they are more easily removed by end-of-pipe abatement measures. Given that China's economy is growing rapidly, China's emissions are decoupling from population, economic, and energy consumption growth (Fig. 2). China's gross domestic product grew by 7.6% per year from 2010 and achieved 67% growth by 2017; however, China's emissions flattened out from 2010–2013, followed by a significant decrease after 2013. In contrast, NMVOC emissions increased by 11% and NH_3 emissions remained flat from 2010–2017; these trends were mainly due to the absence of effective emission control measures.

We present the sectoral trends of China's emissions in Figs. 3 and 4. The most important sector identified by our estimates is the industrial sector, which is the dominant source of SO_2, NO_x, PM_{10}, $PM_{2.5}$, and CO_2 emissions during 2010–2017, accounting for average values of 60%, 38%, 57%, 50%, and 53% of total emissions, respectively. The industrial sector is the driver of changes in 2010–2017 emissions for these pollutants except NO_x and CO_2, and it also drives down CO and BC

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emissions. The power sector, though accounting for more than half of burning coal, is not a dominant contributor to the emissions of any pollutant. The reason for this is that upgrading plants with pollution control equipment in the 11th Five-Year Plan (2006–2010) significantly reduced SO_2 and particulate emissions from power plants (Liu et al., 2015), and the remaining part is not compared to industrial emissions. With upgraded emission standards and the spread of the "ultralow emission" technique, the new emission limit values have further driven down power plant emissions, which is the dominant driving force of the decrease in NO_x emissions, while industrial combustion sources lack an effective control on NO_x.

The residential sector is the dominant source of CO, BC, and OC, to which it contributes average values of 40%, 49%, and 79% to national emissions, respectively, and is the second-most important source of PM_{10} (31%) and $PM_{2.5}$ (38%); its relative contributions of these components have increased while industrial emissions have considerably decreased. The residential sector drives OC emissions down and contributes to the reductions of CO, NMVOC, and particulate matter. The transportation sector accounts for 17% of CO emissions, 19% of NMVOC emissions, and 31% of NO_x emissions. The increase in fuel consumption drives up transport CO_2 emissions, with an increase of 43% from 2010–2017 that is faster than that of any other emission source sector. Solvent use is a major contributor to the increase in NMVOC emissions. Solvent emissions increased by 52% since 2010, making them the largest contributor (37%) to NMVOC emissions in 2017, while the share of this sector was only 27% in 2010. The agricultural sector is the dominant source of NH_3 emissions, as it contributes 93% of total emissions. NH_3 emissions have remained constant because agriculture and rural activities showed small interannual variations.

4.2 Drivers of China's emissions

The effect of air pollution control can partially or totally offset the additional emissions caused by growing activity rates, and the combination of pollution control and activity growth entirely determines China's emission pathways (Fig. 5). Based on the drivers of emissions, we can classify air pollutants into two categories, namely, activity-driven increasing pollutants and pollution control-driven decreasing pollutants (Fig. 5). NMVOC and NH_3 belong to the former category. Their emissions have continued to increase at a constant rate from 2010–2017, primarily driven by activity growth. Assuming that activity rates are frozen at their 2010 levels (Fig. 3), the NMVOC emissions could decrease by 21% from 2010 to 2017 due to the emission controls on residential and transport sectors. These emission reductions were far outweighed by the growing use of solvent for paints and coatings, which consequently drove up their total emissions. The use of solvent for paints increased by 110% from 2010, and the use of solvent for manufacturing chemical products also rose at a fast rate (e.g., ethylene production has grown by 28% since 2010). For NH_3, the lack of control measures has caused its emissions to correlate well with activity; thus, its emissions do not decline similar to the regulated pollutants that have experienced progressive emission control.

The other air pollutants followed distinct emission pathways before and after 2013 (Fig. 5). The emissions of these pollutants slightly increased (e.g., SO_2 and NO_x) or remained flat (e.g., CO and particulate matter) during 2010–2013 because emission mitigation just counterbalanced the additional emissions caused by growing activities. China's fuel combustion increased by

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15.2% from 2010–2013 (Fig. 6), and its industrial production increased by 14–35% in different industries. During this period, China's clean air actions mainly focused on upgrading the emission standards for the power and industrial sectors. These measures effectively offset the growth in activities but were not stringent enough to reverse the growing trends; therefore, air pollutant emissions remained stable from 2010–2013.

After 2013, all air pollutants except NMVOC and NH_3 observed a reduction in emissions driven by pollution control. China's fuel combustion and industrial production have flattened out since 2013 (Fig. 6), while high-efficiency mitigation measures have been increasingly implemented in all emission source sectors, as required by the Clean Air Action. Scenario analysis suggests that the effect of pollution control rapidly removes air pollutants and consequently drives down China's emissions (Fig. 3). Assuming that pollution control is frozen at 2010 levels, SO_2 emissions in 2017 could increase by 167% compared to the actual data, NO_x and TSP emissions could increase by 38% and 111%, respectively, and other pollutants could see increases of 23–66%. The different reduction rates of air pollutant emissions are determined by the source sector distributions and emission mitigation efforts of each sector. For example, this decrease is most notable for SO_2 (emissions decreased by 59% from 2013–2017) because the dominant source sectors (i.e., power and industry) both significantly reduced their emissions. The decrease in emissions is smallest for NO_x (21% of emissions cut from 2013–2017) because the power sector was the major contributor to emission reduction but only accounted for one-third of total emissions. To understand the underlying drivers of emission reduction, we decompose the avoided emissions due to pollution control (i.e., the sum of contributions from $\mathbf{x}$, $\mathbf{E}$, and $\boldsymbol{\eta}$) into sectors (Figs. 7 and 8) to identify the main drivers underlying key source categories. We select the year of 2017, which exhibited the largest reduction in emissions, to perform this analysis.

1) The power sector. The generation of electricity from hydrocarbon fuels in China has increased by 33% since 2010, which has led to increases of 1.2 Tg SO_2 and 1.7 Tg NO_x in 2017 compared with their levels in 2010 (Fig. 7). Mitigation efforts have yielded reductions of 7.1 Tg SO_2 and 6.1 Tg NO_x and thus totally offset the emissions caused by growing activities. The reduction of emissions was achieved through the "ultralow emission" standard. To fulfill the stringent standards, flue gas desulfurization (FGD) and selective catalytic reduction (SCR) systems have been increasingly installed at utilities in coal-fired power plants, with penetration rates reaching >95% in 2017. Of the current power plants, 71% have operated close to the design performance of "ultralow emission" levels (China, 2018).

2) The industrial sector. Mitigation measures have yielded reductions of 9.5 Tg SO_2, 0.9 Tg NO_x, 38.1 Tg CO, 3.4 Tg $PM_{2.5}$, 0.3 Tg BC, and 0.3 Tg OC from the industrial sector in 2017 compared with their levels in 2010 (Fig. 7). For SO_2, shutting small industrial boilers and cleaning larger ones have contributed the most to emission reductions. In particular, small coal boilers (≤7 MW) located in urban areas were eliminated by the end of 2017, and large boilers have extensively used sorbent injection technologies to remove SO_2 from exhaust gases. For other pollutants, the most effective measures include strengthening industrial emission standards, eliminating outdated industrial capacity, and phasing out small and polluted factories. The improvements in combustion efficiency and oxygen blast furnace gas recycling are the largest drivers of declining CO emissions, and the wide use of high-efficiency dust collectors (e.g., electrostatic precipitators and fabric filters) in manufacturing industries has successfully removed particulate matter. In addition, the desulfurization of sinter plant gases

accounts for 8% of SO_2 emission reductions, and denitrification in cement kilns accounts for 6% of NO_x emission reductions. The low-sulfur, low-ash coals resulting from fuel quality improvements have also helped reduce SO_2 and particulate emissions.

3) The residential sector. The emission reductions achieved by the residential sector are primarily driven by the decrease in activities mainly caused by replacing coal with natural gas and electricity (Fig. 7), which yielded reductions of 13.5 Tg CO, 1.0 Tg $PM_{2.5}$, 0.1 Tg BC, and 0.7 Tg OC in 2017 compared with their 2010 levels. Additionally, pollution controls caused additional reductions of 0.5 Tg CO, 0.3 Tg $PM_{2.5}$, 0.1 Tg BC, 0.1 Tg OC, and 1.0 Tg SO_2. The decreases in activity rates reflect both long-term changes in fuel mixtures, i.e., from traditional biofuels to commercial energy, and short-term measures to replace coal with clean energy. Pollution control policies have promoted the use of clean stoves and the switch from raw coal to clean coal briquettes with lower levels of sulfur and ash.

4) The transportation sector. Pollution controls on the transportation sector have exactly counterbalanced the growing emissions due to vehicle growth (Fig. 7). China's vehicle ownership reached 209 million in 2017; this value is 2.7 times larger than its 2010 value. Growing activities yielded increases of 22.2 Tg CO, 3.6 Tg NMVOC, and 1.4 Tg NO_x in 2017 compared with their 2010 levels, while pollution control measures have yielded reductions of 29.0 Tg CO, 4.8 Tg NMVOC, and 1.3 Tg NO_x. The reduction of emissions is mainly achieved through fleet turnover, which means that old vehicles are being replaced by newer, cleaner models subjected to tougher emission standards. The estimated share of fuel consumption by Euro 4 and Euro 5 vehicles increased from 2% in 2010 to 66% in 2017, and all "yellow label" vehicles have been eliminated. The effects of these changes on reducing particulate emissions is smaller, because transport contributes only a small fraction of total particulate emissions. For NMVOC, the transport sector is the only sector that has seen a deep cut in emissions. More than 80% of NMVOC emission reductions are achieved from tailpipe exhaust sources, which have caused evaporative emissions to be the primary source (>60%) of the remaining NMVOC emissions from transport.

4.3 Comparison with observations

The 2010–2017 trends in NO_x and SO_2 emissions are consistent with OMI satellite observations (Fig. 8a). During the entire study period, NO_x emissions from Eastern China decreased by 20%, which is close to the 26% decrease observed in the OMI NO_2 columns, and the percent changes in SO_2 emissions and OMI SO_2 columns were −67% and −73%, respectively. The rapid declines of NO_x and SO_2 have only occurred since 2013, as was also evident from ground-based measurements in cities (Fig. 8b). From 2013 to 2017, the nationally averaged urban concentrations of NO_2 and SO_2 decreased by 9% and 57%, respectively, mainly due to a 21% decrease in NO_x emissions and a 59% decrease in SO_2 emissions. The national average NO_2 and SO_2 concentrations are calculated from the observation sites located in 74 cities over China that have provided continuous measurements since 2013. The concentration changes measured within these cities are broadly consistent with the overall decreasing trends in national SO_2 emissions, while the NO_2 concentrations have seen a smaller decrease than NO_x emissions. The reason for this trend is that the power sector is responsible for all NO_x emission reductions, while this sector would have little effect on cities' NO_2 pollution because power plants are often located far away from urban regions. The

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increasing or flattening emissions from other source sectors may contribute to the stalling of NO_2 concentrations in cities. Our estimates of these emission trends also agree well with other published estimates obtained from satellite observations and inverse modeling (Table 2).

5 Concluding Remarks

From 2010–2017, China reduced its anthropogenic emissions by 62% for SO_2, 17% for NO_x, 27% for CO, 38% for PM_{10}, 35% for $PM_{2.5}$, 27% for BC, and 35% for OC. Most of these emission reductions were achieved after 2013, when the government accelerated its clean air actions to improve air quality. Index Decomposition Analysis confirms that emission control measures have been the dominant driver of this declining emission trend. Pollution controls on the power and industrial sectors are the most effective measures, which have contributed to 56–94% of total avoided emissions due to stringent mitigation policies, such as strengthening emission standards, eliminating outdated industrial capacity, and phasing out small and polluted factories. Emissions from transport tend to remain flat because the effect of air pollution control is offset by the additional emissions from growing activities. The residential sector has mainly reduced its emissions through the substitution of clean fuels. The declining trends in NO_x and SO_2 emissions are consistent with both OMI satellite and ground-based observations. From 2010–2017, NMVOC emissions increased by 11% and NH_3 emissions flattened because China lacked effective emission control measures for NMVOC and NH_3 in its current policies.

With decreasing emissions, the contributions of once-dominant source sectors have decreased, and emissions from other sources have gradually occupied larger proportions (Fig. 9). The change in the sectoral distribution of emissions indicates that it is paramount to shift policy focus to enable the further mitigation of emissions. China's clean air policies have had limited effects on reducing emissions from the residential, off-road, solvent use, and agricultural sectors until the present. These sectors have significantly increased their contributions from 2010 to 2017 (Fig. 9); therefore, China needs to increase its focus on these sectors from now on. For example, the residential sector accounted for 23–50% of SO_2 and particulate emissions in 2017, comparable to or even larger than the emissions of the power and industrial sectors. The contribution of off-road transport to NO_x emissions increased from 8% to 12% (Fig. 9b) and thus ranked as the fourth largest single sector in 2017. A wide range of solvent-using activities drove up NMVOC emissions, and solvent use ranked as the largest source sector (Fig. 9d). The agricultural sector currently lacks targets, policies and measures to control NH_3 emissions. These less-controlled emission sources will have great potential effects on China's air quality; thus, more attention must be paid to them in the future.

Data availability

The bottom-up emission inventory presented in this paper can be accessed from http://www.meicmodel.org.

Acknowledgements

This work was supported by the National Key R&D program (2016YFC0201506 and 2016YFC0208801), the National Natural Science Foundation of China (41625020, 91744310, and 41571130035), and the public welfare program of China's Ministry of Environmental Protection (201509004).

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<table>
<tr><th>Source sector</th><th>Emission source</th><th>2010</th><th>2011</th><th>2012</th><th>2013</th><th>2014</th><th>2015</th><th>2016</th><th>2017</th></tr>
<tr><td>Power</td><td>Thermal power plants</td><td colspan="2">GB 13223-2003</td><td colspan="4">GB 13223-2011</td><td colspan="2">“ultra-low” emission standard</td></tr>
<tr><td rowspan="10">Industry</td><td>Flat glass</td><td>No standards</td><td colspan="7">GB 26453-2011</td></tr>
<tr><td>Sinter</td><td colspan="2">No standards</td><td colspan="6">GB 28662-2012</td></tr>
<tr><td>Iron</td><td colspan="2">No standards</td><td colspan="6">GB 28663-2012</td></tr>
<tr><td>Steel making</td><td colspan="2">No standards</td><td colspan="6">GB 28664-2012</td></tr>
<tr><td>Steel rolling</td><td colspan="2">No standards</td><td colspan="6">GB 28665-2012</td></tr>
<tr><td>Electronic glass</td><td colspan="3">No standards</td><td colspan="5">GB 29495-2013</td></tr>
<tr><td>Brick</td><td colspan="4">No standards</td><td colspan="4">GB 29620-2013</td></tr>
<tr><td>Cement</td><td colspan="4">GB 4915-2004</td><td colspan="4">GB 4915-2013</td></tr>
<tr><td>Industrial boiler</td><td colspan="4">GB 13271-2001</td><td colspan="4">GB 13271-2014;
Eliminate small coal-fired boilers.</td></tr>
<tr><td>All</td><td colspan="3">/</td><td colspan="5">Phase out outdated industrial capacity; Strengthen emissions standards; Phase out small and polluted factories; Install VOC emission control facilities</td></tr>
<tr><td>Residential</td><td>All</td><td colspan="3">No specific regulations</td><td colspan="5">Replace coal with electricity and natural gas</td></tr>
<tr><td rowspan="4">Transportation</td><td>Light duty gasoline vehicle</td><td>Euro 3</td><td colspan="6">Euro 4</td><td>Euro 5</td></tr>
<tr><td>Heavy duty gasoline vehicle</td><td colspan="3">Euro 3</td><td colspan="5">Euro 4</td></tr>
<tr><td>Diesel vehicle</td><td colspan="4">Euro III</td><td colspan="3">Euro IV</td><td>Euro V</td></tr>
<tr><td>All</td><td colspan="3">/</td><td colspan="5">Strengthen emissions standards; Retire old vehicles; Improve fuel quality</td></tr>
</table>

Figure 1. China’s clean air policies implemented from 2010–2017.

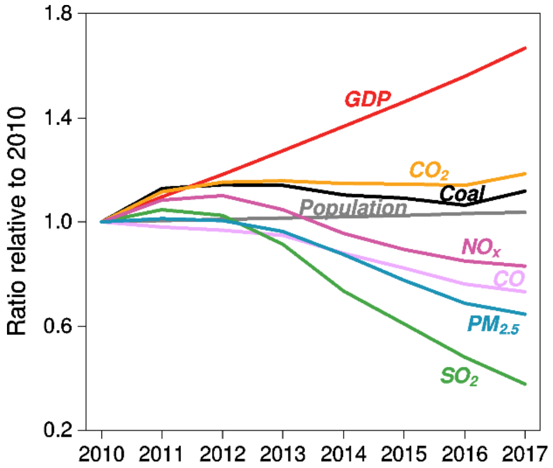

Figure 2. Emission trends and underlying social and economic factors. The coal usage are achieved from Chinese Energy Statistics (National Bureau of Statistics, 2018a, 2018b). The GDP and population data come from National Bureau of Statistics (2018b, 2018c). Data are normalized by dividing the values of each year by their corresponding value during the year 2010.

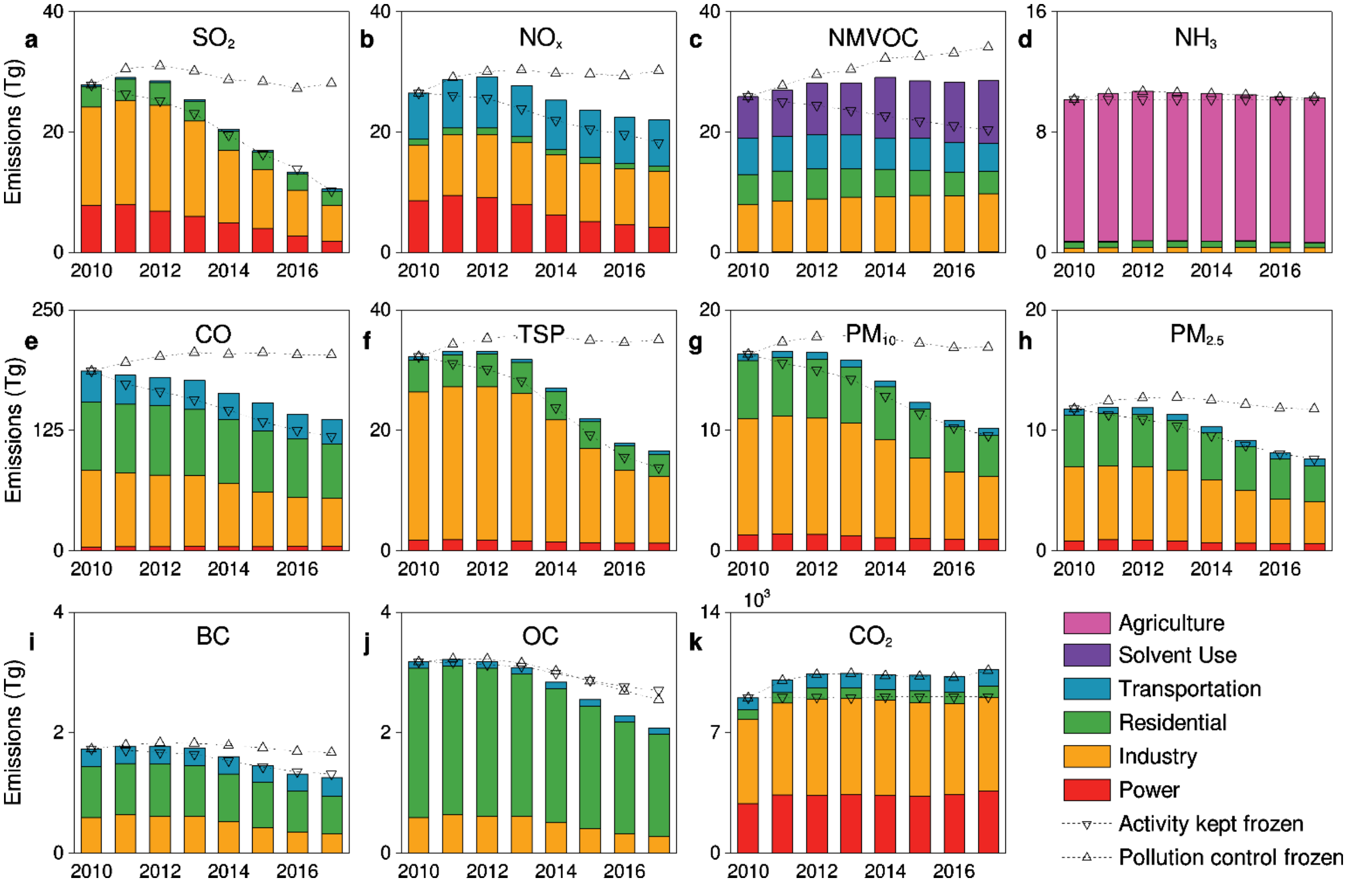

Figure 3. China's anthropogenic emissions by sector and year. The species plotted here include (a) SO_2, (b) NO_x, (c) NMVOC, (d) NH_3, (e) CO, (f) TSP, (g) PM_{10}, (h) $PM_{2.5}$, (i) BC, (j) OC, and (k) CO_2. China emissions are divided into six source sectors (stacked column chart): power, industry, residential, transportation, agriculture, and solvent use. Besides the actual emissions data, two emission scenarios are presented to provide emission trajectories when assuming activity (inverted triangle) or pollution control (upright triangle) frozen at 2010 levels.

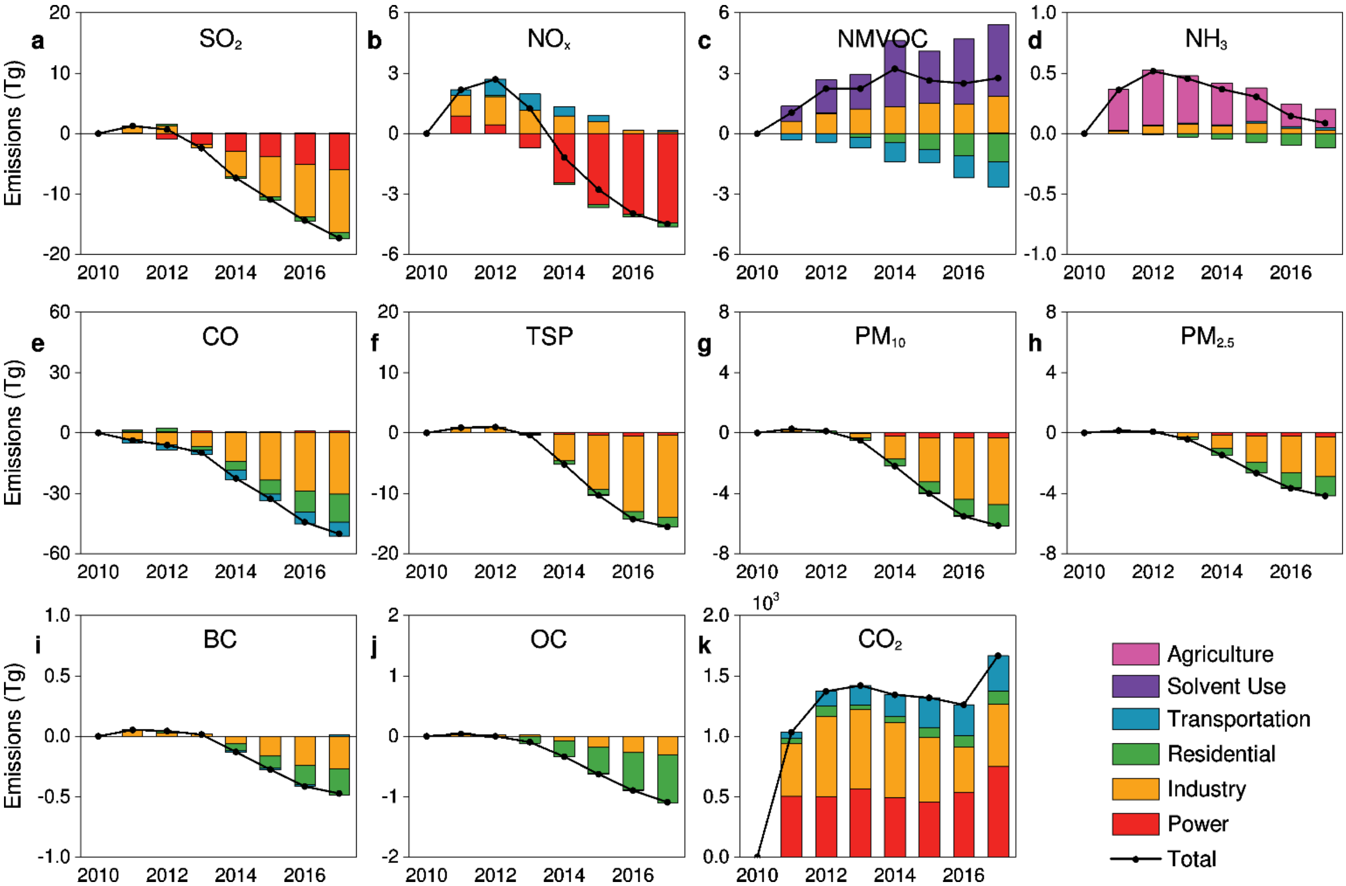

Figure 4. Changes in China's emissions by sector and year. The species plotted here include (a) SO_2, (b) NO_x, (c) NMVOC, (d) NH_3, (e) CO, (f) TSP, (g) PM_{10}, (h) $PM_{2.5}$, (i) BC, (j) OC, and (k) CO_2. The 2010 emissions are subtracted from the emission data for each year to represent the additional emissions compared to 2010 levels. The emission changes are shown by sector (stacked column chart) and as national totals (black curve).

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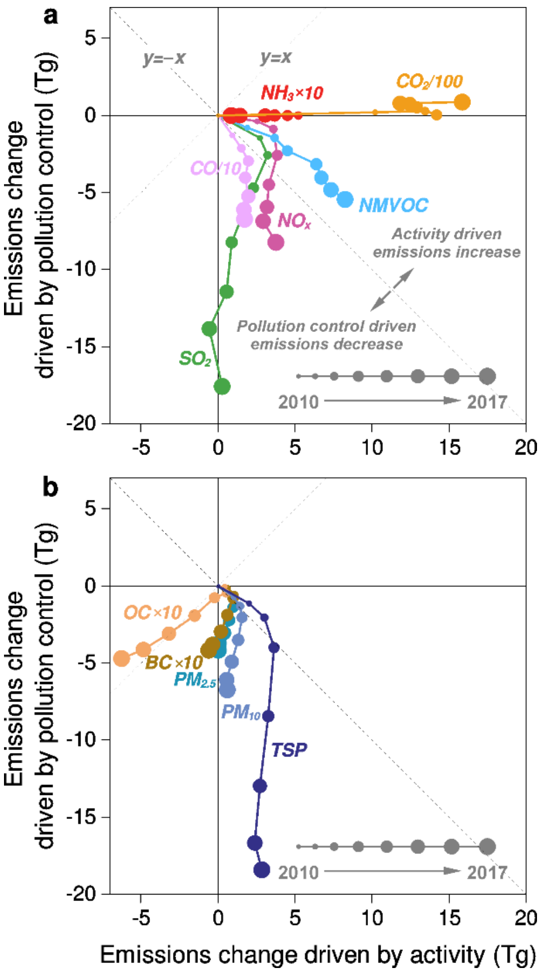

Figure 5. China's emission pathways from 2010–2017. Gaseous pollutants are plotted in (a), and particles are plotted in (b). For each pollutant, the years (circle) are plotted according to the emission changes caused by activity (*A* in Eq. (2), x-axis) and pollution control (the sum of **x**, **E** and **η** in Eq. (2), y-axis). Please refer to Fig. S1 for decomposition analysis results of *A*, **x**, **E** and **η**. The intersecting lines y=x and y=−x divide the coordinate plane into four sections. Any point in the section on the right side of the two lines reflects increasing emissions due to activity growth, and the points in the section below the two lines reflect decreasing emissions driven by pollution control.

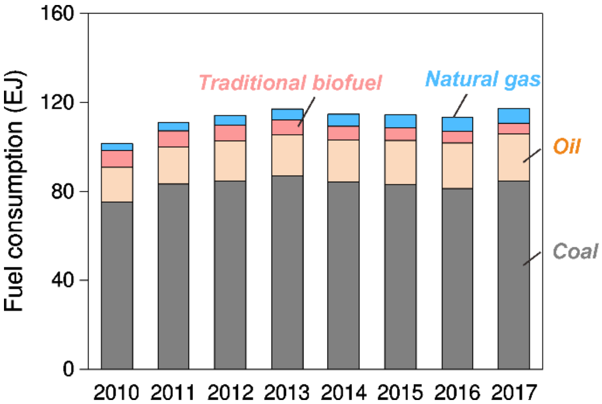

Figure 6. Energy consumption of hydrocarbon fuels from 2010 to 2017. Coal includes all coal-based fuels, and oil includes all oil-based fuels. Traditional biofuel includes crop residual and wood.

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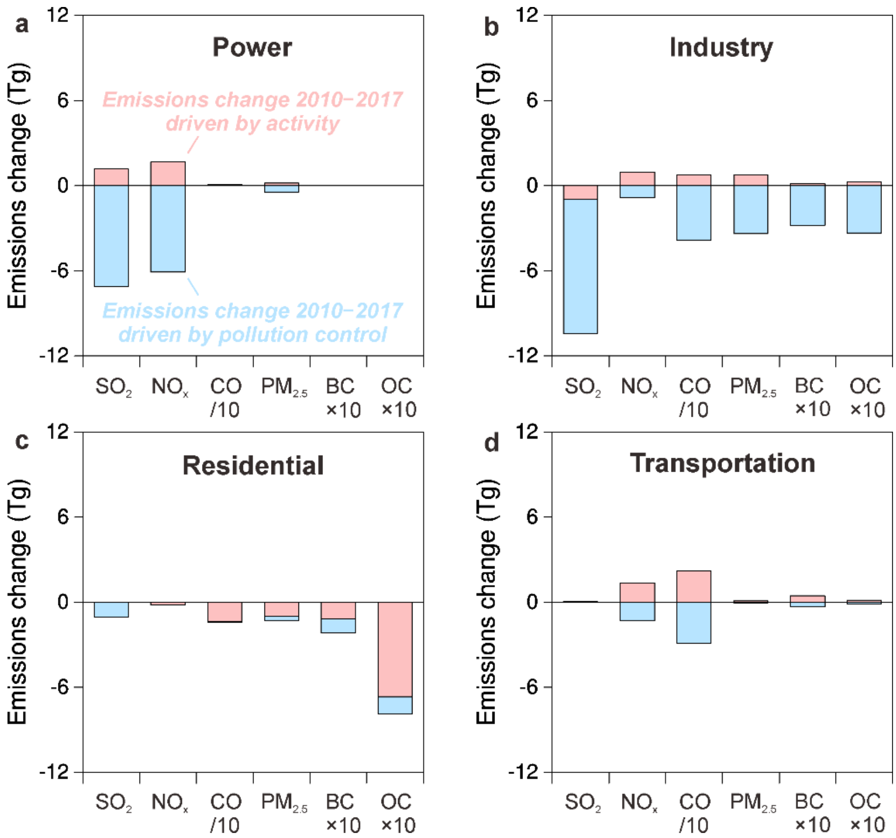

Figure 7. Drivers of emission changes for different source sectors. The sectors plotted here include (a) power, (b) industry, (c) residential, and (d) transportation. For each sector, the changes in emissions from 2010 to 2017 (bar) are plotted according to air pollutants (x-axis) and the changes in emissions driven by activity (*A* in Eq. (2), red bar along y-axis) and pollution control (the sum of **x**, **E** and **η** in Eq. (2), blue bar along y-axis).

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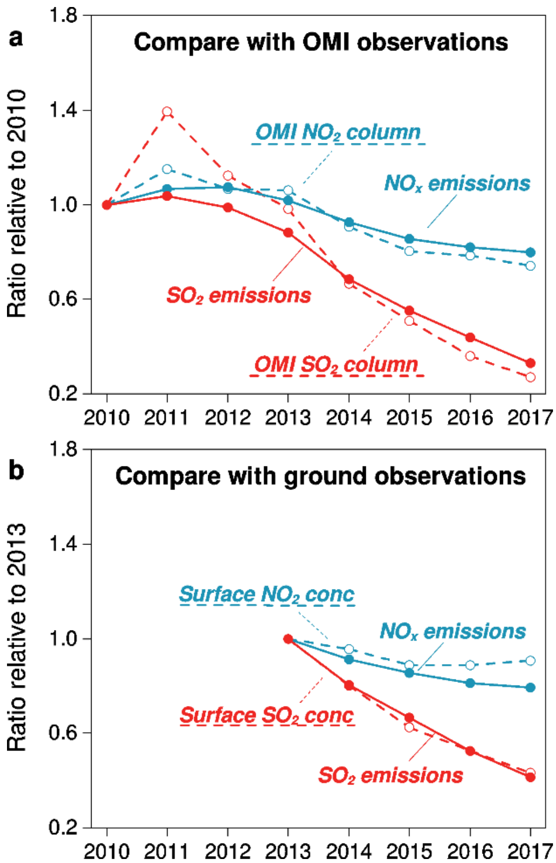

Figure 8. Emission trends compared with OMI and ground observations. The 2010–2017 trends in SO_2 (red, solid curve in a) and NO_x (blue, solid curve in a) emissions are compared with OMI SO_2 (red, dashed curve in a) and NO_2 (blue, dashed curve in a) tropospheric columns, respectively. Besides, the 2013–2017 trends in SO_2 (red, solid curve in b) and NO_x (blue, solid curve in b) emissions are compared with ground-based in situ observations of SO_2 (red, dashed curve in b) and NO_2 (blue, dashed curve in b), respectively.

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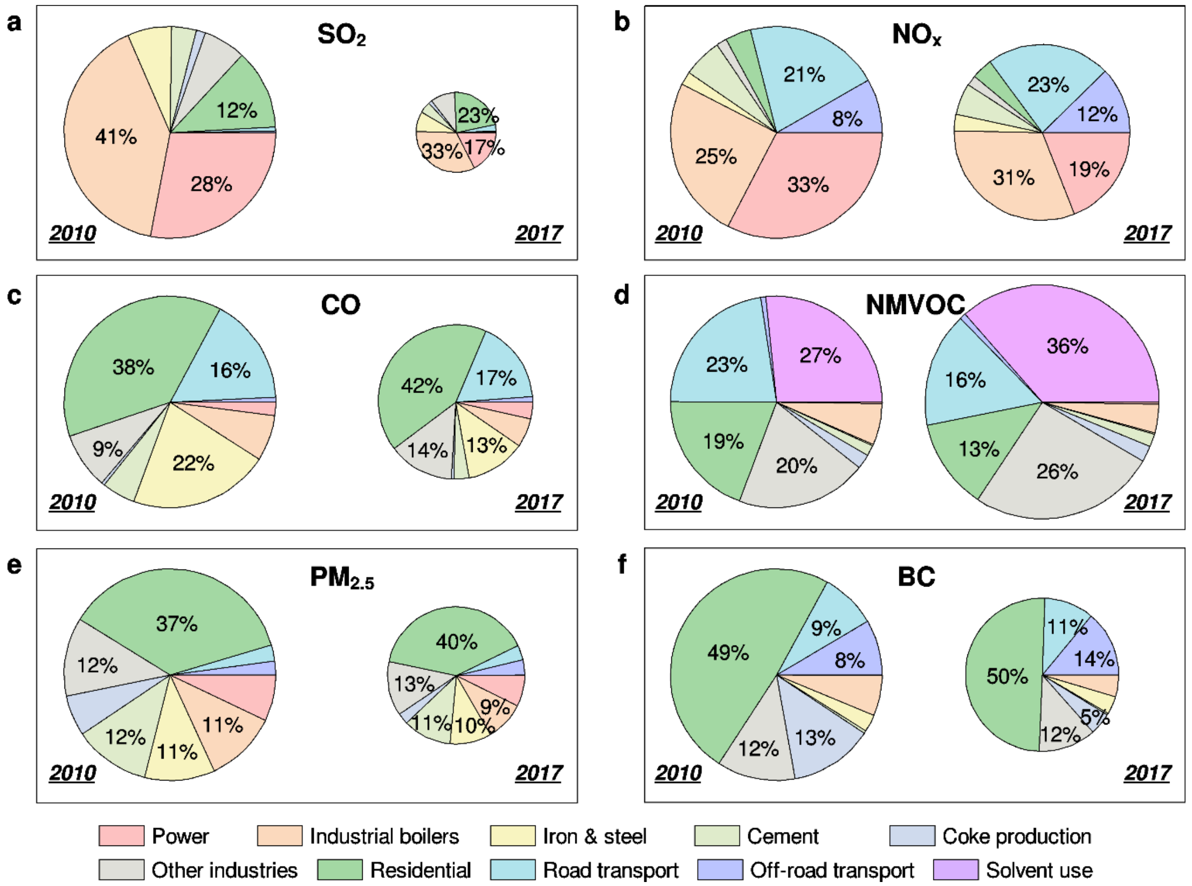

Figure 9: Changes in emission percentages across source sectors from 2010 to 2017. The species plotted here include (a) SO_2, (b) NO_x, (c) CO, (d) NMVOC, (e) $PM_{2.5}$, and (f) BC. For each pollutant, the relative change in the radius of the pie chart from 2010 to 2017 is proportional to the change in emissions.

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Table 1: Anthropogenic emissions of air pollutants and CO_2 in China from 2010 to 2017.

Year	SO_2[a]	NO_x	NMVOC	NH_3	CO	TSP[b]	PM_{10}	$PM_{2.5}$	BC	OC	CO_2[c]
Power	7.8	8.6	0.1	0.0	3.8	1.7	1.3	0.8	0.0	0.0	2864.8
Industry	16.4	9.1	7.9	0.3	79.7	24.7	9.6	6.1	0.6	0.6	4914.3
Residential	3.4	1.0	5.0	0.4	70.9	5.3	4.8	4.3	0.8	2.5	567.8
Transportation	0.2	7.7	6.1	0.0	32.0	0.6	0.5	0.5	0.3	0.1	682.5
Agriculture	0.0	0.0	0.0	9.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solvent use	0.0	0.0	6.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2010	27.8	26.5	25.9	10.2	186.4	32.2	16.3	11.8	1.7	3.2	9029.4
Power	7.9	9.5	0.1	0.0	4.4	1.8	1.4	0.9	0.0	0.0	3365.2
Industry	17.3	10.2	8.5	0.3	76.3	25.4	9.8	6.2	0.6	0.6	5354.7
Residential	3.6	1.1	5.0	0.4	71.6	5.3	4.9	4.3	0.9	2.5	609.9
Transportation	0.3	8.0	5.8	0.0	30.2	0.5	0.5	0.5	0.3	0.1	735.7
Agriculture	0.0	0.0	0.0	9.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solvent use	0.0	0.0	7.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2011	29.1	28.7	26.9	10.5	182.7	33.1	16.6	11.9	1.8	3.2	10065.5
Power	6.9	9.1	0.1	0.0	4.5	1.7	1.3	0.9	0.0	0.0	3361.3
Industry	17.6	10.5	8.9	0.3	74.0	25.5	9.7	6.1	0.6	0.6	5584.5
Residential	3.7	1.1	5.0	0.4	72.4	5.4	4.9	4.4	0.9	2.5	652.1
Transportation	0.3	8.5	5.6	0.0	29.4	0.6	0.5	0.5	0.3	0.1	802.2
Agriculture	0.0	0.0	0.0	9.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solvent use	0.0	0.0	8.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2012	28.5	29.2	28.1	10.7	180.2	33.2	16.5	11.9	1.8	3.2	10400.1
Power	6.0	7.9	0.1	0.0	4.7	1.6	1.3	0.8	0.0	0.0	3431.0
Industry	15.8	10.3	9.1	0.4	72.9	24.6	9.3	5.8	0.6	0.6	5569.9
Residential	3.4	1.0	4.8	0.4	69.3	5.1	4.7	4.2	0.8	2.4	600.6
Transportation	0.3	8.5	5.6	0.0	29.8	0.6	0.5	0.5	0.3	0.1	849.4
Agriculture	0.0	0.0	0.0	9.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solvent use	0.0	0.0	8.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2013	25.4	27.7	28.1	10.6	176.6	31.8	15.8	11.4	1.7	3.1	10450.9
Power	4.9	6.2	0.1	0.0	4.5	1.4	1.1	0.7	0.0	0.0	3359.4
Industry	12.1	10.0	9.2	0.3	65.4	20.3	8.1	5.2	0.5	0.5	5530.3
Residential	3.1	0.9	4.5	0.4	66.7	4.8	4.4	3.9	0.8	2.2	620.1
Transportation	0.3	8.1	5.1	0.0	27.2	0.5	0.5	0.5	0.3	0.1	864.0
Agriculture	0.0	0.0	0.0	9.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solvent use	0.0	0.0	10.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2014	20.4	25.3	29.1	10.5	163.8	27.0	14.1	10.3	1.6	2.8	10373.8

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-374
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 2 May 2018

Power	3.9	5.1	0.1	0.0	4.5	1.3	1.0	0.6	0.0	0.0	3318.7
Industry	9.8	9.7	9.4	0.4	56.2	15.7	6.7	4.4	0.4	0.4	5450.0
Residential	2.9	0.9	4.2	0.4	64.0	4.4	4.1	3.6	0.7	2.0	651.5
Transportation	0.3	8.0	5.4	0.0	28.9	0.5	0.5	0.5	0.3	0.1	926.9
Agriculture	0.0	0.0	0.0	9.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solvent use	0.0	0.0	9.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2015	16.9	23.7	28.5	10.5	153.6	21.9	12.3	9.1	1.5	2.5	10347.2
Power	2.7	4.6	0.1	0.0	4.6	1.3	1.0	0.6	0.0	0.0	3399.9
Industry	7.7	9.3	9.3	0.3	50.8	12.1	5.6	3.7	0.3	0.3	5290.1
Residential	2.7	0.9	3.9	0.3	60.4	4.0	3.7	3.3	0.7	1.9	661.9
Transportation	0.3	7.7	5.0	0.0	26.2	0.5	0.5	0.5	0.3	0.1	938.8
Agriculture	0.0	0.0	0.0	9.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solvent use	0.0	0.0	10.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2016	13.4	22.5	28.4	10.3	141.9	17.9	10.8	8.1	1.3	2.3	10290.6
Power	1.8	4.2	0.1	0.0	4.8	1.3	1.0	0.6	0.0	0.0	3615.8
Industry	6.0	9.2	9.7	0.3	49.2	11.1	5.2	3.5	0.3	0.3	5430.8
Residential	2.4	0.8	3.6	0.3	57.0	3.7	3.4	3.0	0.6	1.7	671.9
Transportation	0.3	7.7	4.8	0.0	25.2	0.6	0.6	0.5	0.3	0.1	977.6
Agriculture	0.0	0.0	0.0	9.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Solvent use	0.0	0.0	10.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2017	10.5	22.0	28.6	10.3	136.2	16.7	10.2	7.6	1.3	2.1	10696.1
(2013−2010)/2010	−9%	5%	9%	4%	−5%	−1%	−3%	−4%	1%	−3%	16%
(2017−2013)/2013	−59%	−21%	2%	−3%	−23%	−48%	−36%	−33%	−28%	−32%	2%
(2017−2010)/2010	−62%	−17%	11%	1%	−27%	−48%	−38%	−35%	−27%	−35%	18%

[a] The unit of emissions is Tg. [b] TSP is particulate matter with aerodynamic diameter of 100 μm or less. [c] CO_2 from fossil fuel use and industrial processes.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-374
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 2 May 2018

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Table 2: Comparison of trends in bottom-up emission inventory, satellite-based observations, and top-down emission estimates since 2010.

Pollutant	Study	Method[a]	Data	Region[b]	Period	Percent change (%)	Percent change of emissions in this study (%)
SO_2	Krotkov et al. (2016)	SAT	OMI SO_2 columns	E China	2010–2015	−48	−45
	van der A et al. (2017)	SAT	OMI SO_2 columns	China	2010–2015	−34	−39
	Li et al. (2017a)	IM	SO_2 emissions	China	2010–2016	−71	−52
	Koukouli et al. (2018)	IM	SO_2 emissions	China	2010–2015	−27	−39
NO_x	Krotkov et al. (2016)	SAT	OMI NO_2 columns	E China	2010–2015	−22	−14
	Liu et al. (2016)	SAT	OMI NO_2 columns	E China	2010–2015	−22	−14
	de Foy et al. (2016)	SAT	OMI NO_2 columns	China	2010–2015	−12	−10
	van der A et al. (2017)	IM	NO_x emissions	E China	2010–2015	−8	−14
	Miyazaki et al. (2017)	IM	NO_x emissions	China	2010–2015	−4	−10
NH_3	Warner et al. (2017)	SAT	AIRS NH_3 VMR[c]	China	2010–2016	9	1
CO	Jiang et al. (2017)	IM	CO emissions	E China	2010–2015	−13~−9	−18
	Zheng et al. (2018)	IM	CO emissions	China	2010–2016	−25	−24

[a] SAT=satellite-based observations; IM=inverse modeling. [b] E China=Eastern China; [c] VMR=volume mixing ratio.