Reviewer #1:

Comments:

This paper is important documentation of the strong air pollution policies in China in the last decade and their consequences on emissions. It comes at the time when new set of scenarios for the IPCC AR6 Report are being finalized and they should take into account these changes, especially for aerosols where climate impacts are or larger significance.

Response:

We thank the reviewer #1 for the constructive comments and address them as below.

While the estimated emission trends largely coincide with several recent papers reporting observations, the very rapid decline in SO_2, especially in the last 2-3 years, appears even stronger here than some of the observations and it is interesting that there seem to be very little (if any) impact on $PM_{2.5}$ concentrations in the last few years. Of course no direct translation of SO_2 trends to $PM_{2.5}$ are expected but bearing in mind that apart from NMVOC all other species are reported to either slightly decline or staying constant, it is a bit of a surprise. I think this deserves a bit more discussion which might bring the issues like regional distribution of changes or stack height into it. I'd welcome a general discussion not necessarily very detailed one that would probably fit in the section 4.3, which is very short now.

Response:

Satellite-derived $PM_{2.5}$ concentrations were flat over China during 2010 and 2013 (Fig. 8a), corresponding to small variations in emissions of different precursors estimated for the same period. Satellite-based $PM_{2.5}$ concentrations decreased by 18% from 2013–2015, in good agreement with trend in surface $PM_{2.5}$ concentrations over 74 cities in China. During 2013–2017, surface $PM_{2.5}$ concentrations over 74 cities decreased by 35%. We estimated faster decrease in SO_2 emissions (−59%) than observed surface $PM_{2.5}$ concentrations, while the estimated decrease rates of NO_x (−21%) and NH_3 (−3%) emissions were slower than observed $PM_{2.5}$ concentrations. This phenomenon was qualitatively confirmed by observed large decrease of sulfate and increased relative contribution of nitrate and ammonium in $PM_{2.5}$ compositions from 2013–2017 (Shao et al., 2018). We added a discussion on the trend of $PM_{2.5}$ concentrations and the relation to estimated emissions in Sect. 4.3 as the reviewer suggested.

The other element that is not discussed are the uncertainties. There are several elements which are uncertain in the process of estimating emissions and their trends, including the past (not always good) experience in official data reporting and of course the interpretation of remote sensing data, e.g, the quality or ability of monitoring high stack emissions versus low level sources' changes.

Response:

We add a discussion in Sect. 4.3 to discuss the uncertainties in OMI retrievals and in emission estimates, as well as their influence on comparison between emission trends and observations. Please refer to Sect. 4.3 in the revised manuscript for more details.

I think the paper is well written and has good illustrations. It also includes all key references that I would know of; referring to my comments above I would suggest to add few for the potential discussion (reference to) of particulate matter trends and relation to the emission trends discussed here.

Response:

We add a discussion on the trend of $PM_{2.5}$ concentrations and the relation to estimated emissions in Sect. 4.3. Please refer to the response to the 1st comment.

Few more detailed comments:

Page 2, line 1-6: This paragraph includes reference to short lived climate forces and climate, fine, but I'd suggest to review the text and rewrite it slightly as while the authors list PM, ozone and SLCF then in the following impact statement they do not mention regional climate change. It is mentioned later in bold way how they contribute to local and regional ecosystems impacts as well as climate change...but the latter is really CO_2 and CH_4 in the first place and not pollutants. Yes, SO_2 has an important role but its trajectory is not going to fix (tackle) or screw the climate issue.

Response:

We rewrite this paragraph to add the statement of regional climate change as follows.

"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 regional climate. These pollutants not only cause local to regional environmental problems such as premature deaths and agricultural yield losses, but also have significant impact on regional climate changes in temperature and precipitation. To tackle the problems of both air pollution and regional climate change, it is important to fully understand the trends and drivers of Chinese emissions."

Page 2, line 11: ' WHO acceptable standards' - be specific to what you refer, I'd suggest changing the wording and say which standard you mean and give reference. Then also the reference in the next sentence to 'this AQ standard' will be clear.

Response:

Corrected.

Page 3, line 23: The reference to China (2018); is this including, referring to actual continuous measurement data or an assessment based on the plant operator and regional reports? I think it *makes a bit difference in view of the credibility of these. The ref alone does not appear verifiable. Adding few words and certainty and validation of this would be desired.*

Response:

The reference to China (2018) suggests that 71% of installed capacity of power plants operated close to "ultralow emission" levels in 2017. This figure is estimated on the basis of firm-level information of pollution control devices and efficiencies, which are collected from each plant by local agencies, and then managed and verified by Ministration of Environmental Protection of China. The power plants that comply with "ultralow emission" standards are mainly large ones at the current stage. Most of them use continuous emission monitoring systems to monitor exhaust emissions, which confirm that these plants are indeed complying with the "ultralow" emission standards. We add a discussion on the credibility of China (2018) to make the statement stronger.

Page 4, line 1-2: '...covered all emission intensive industries...' To make the statement stronger I'd suggest to add something about embedded enforcement in this regulation and how did it (or not) worked in the past/so far.

Response:

We now added examples of cement plants and industrial boilers to this paragraph to illustrate the enforcement of emission limits. The emission limits of cement plants were 800 mg m^{-3} for NO_x and 50 mg m^{-3} for particulates before 2014 (the standard GB 4915-2004), while after 2014 all cement plants were required to reach new limit values of 400 mg m^{-3} for NO_x and of 30 mg m^{-3} for particulates (the standard GB 4915-2013). For coal boilers used in all of the types of industries, the emission limits were 900 mg m^{-3} for SO_2 and 80–250 mg m^{-3} for particulates before 2014 (the standard GB 13271-2001), and no limits were required for NO_x. After 2014, new coal-fired industrial boilers faced stricter limit values of 300, 300 and 50 mg m^{-3} for SO_2, NO_x and particulates (the standard GB 13271-2014), respectively. The introduction of new emission standard in 2014 also tightened limit values for the existing coal-fired industrial boilers, where the "not to exceed" limits for SO_2, NO_x and particulates were 400, 400 and 80 mg m^{-3}, respectively.

Page 4, line 23-24: It is unclear to what is this referring (the economy standards); is this the sticker value given on produced cars or it is real change in the average on the road? My reading would be this is the sticker value for new sold cars and so not necessarily reflecting the real life change at least for two reasons: Real life consumption is somewhere 20-30% higher and in the urban cycle even more, the fleet composition will affect the true impact of such 'sticker' value change. Few words of clarification would be useful in the paper.

Response:

True. China's economy standards refer to the fuel consumption rates of vehicles tested under the European standard driving cycle in laboratory. The tested fuel efficiency are shown on fuel economy labels (window stickers) of new sold cars. The real-world fuel consumption rates are typically 15% higher than these sticker values (Huo et al., 2011), because the European test procedure cannot reflect the real urban and highway driving conditions in China. We clarify these in the revised manuscript.

Page 7, line 8; I am not able to access this http address. The Sliverlight needs to be installed it says but when I try to do it, I get a message that I actually have it (tried on few browsers) and it is not allowed to install again...but effectively I cannot access and view anything from the link. Could you check please?

Response:

I can access the URL of http://106.37.208.233:20035/ using Internet Explorer. I tried two different computers (Windows 7 system) and accessed this website after installing Silverlight. If that doesn't work for you, you can also view the archived observational data at the website of http://beijingair.sinaapp.com/.

Page 8, line 26: I guess it is not only paints and coatings that contribute to strong growth of NMVOC emissions. The whole chemical industry is responsible and there is more to it than just paints. Please verify and adjust if appropriate.

Response:

NMVOC emissions from paints and coatings increased by 2.4 Tg from 2010–2017, which are the largest contributor to the growth of 2.7 Tg emissions from all source sectors. The strong growth of paints can be attributed to the increasing demand to coat buildings, cars, and machinery due to the rapid increase in the area of newly built house (+52%) and the production of vehicles (+54%). Chemical industry increased 1.5 Tg NMVOC emissions from 2010–2017, making them the second largest contributor to NMVOC growth. We clarify this in the manuscript.

Page 9, line 13 and 18: the authors use words" 'decreased' and 'exhibited' but I'd say rather 'are estimated to decline' ' were estimated ' ... since these are still estimates not entirely free from uncertainties.

Response:

Corrected.

Page 9: There is no specific reference to sectors like bricks and coke manufacturing for which there are no or very few unpublished estimates of actual emissions so how changes/transformation in these sectors included/evaluated? In general the fact that most reductions were estimated to take place in industry, including small industries, the question about monitoring and enforcement arises. It goes without saying that it is harder to monitor progress in policy implementation over 100s thousands sources vs power plant sector for example. I think the paper needs some, even if brief' discussion of this.

Response:

Brick and coke manufacturing industries have seen strict emissions standards since 2010 (Fig. 1), and pollutants generated by these regulated sources are monitored and managed by local agencies.

Each province submits annual implementation report to China's Ministry of Environmental Protection to summarize the progress in pollution control every year, and we derived the information of emission changes from those reports. These are the best data sources available now, but we still agree that the statistics for thousands of small industrial sources tend to be more uncertain than the large industries that have good record in pollution levels. We summarize these information in Sect. 4.3, and discuss the difficulty to monitor progress in pollution control over small industries and its influence on uncertainties of emission trend estimates.

Page 10, line 15: 'old vehicles' - I was wondering what happens to them. Are they scrapped or they move to poorer remote provinces? Is there a record of that? Can you add a statement about the fate of these scrapped vehicles? I think this could reinforce the confidence of readers.

Response:

China has scrapped all the old vehicles that don't meet stringent emission standards, i.e., "yellow label" vehicles, by the end of 2017. The number of vehicles scrapped in each province are recorded by local government, and these scrapped vehicles are banned from roads and sent to wrecking yard for recycling. We clarify this in the revised manuscript.

Page 10, section 4.3: As mentioned earlier I'd welcome more discussion here, including uncertainty in OMI retrievals, few more words about the studies quotes as SAT or IM in Table 2 as some of them appear to be OMI related studies but you choose to use the IM component of those - something that was not clear to me first. Then there is issue of $PM_{2.5}$ observations and virtually lak or very small signal visible there - Example of studies where some of the trends are discussed could include: Fei Yao et al (2018; Sci of Tot Env), Fengchao Liang et al (2018, Sco of Tot Env), Rong Xie et al. (2016, Env International), Haifeng Zhang et al (2016, Env Pollution), Tania Fontes et al (2017, J. of Env Management), Xiaoyan Wang et al (2018, Amer Met Soc); Li and Sun (2018, A Economy and Space), C.Q. Lin et al (2018, Atm Env). Also in reference to the above and Figure 8; few more words of explanation there and uncertainties associated with it would be very useful. Actually amazing agreement shown here for recent trends (seems certain) while for 2011 strange 'anomaly' ; how well OMI captures changes in emissions of small low level sources like industries or residential coal versus high level stacks - an issue that potentially can lead to overestimation of strong decline in overall emissions.

Response:

For the IM studies in Table 2, we clarify the satellite observations they used to constrain emissions, including OMI columns of SO_2 and NO_2 and MOPITT CO columns.

We add a discussion on the trend of $PM_{2.5}$ concentrations and their relation to the estimated emissions in Sect. 4.3. The correlation between $PM_{2.5}$ concentrations and emissions of $PM_{2.5}$ precursors are analyzed, and the associated uncertainties are discussed. For more details please refer to the revised manuscript.

The uncertainty in using OMI retrievals to infer emissions is also discussed in Sect. 4.3. Interannual variabilities can result in remarkable variations in column concentrations (Uno et al., 2007), which may partly explain the disagreement between changes in emissions and observations for a signal year (e.g., year 2011 in Fig. 8b). In addition, satellite-based column observations are typically more visible to high-stack emissions. For example, SO_2 columns are less sensitive to small and near surface emissions (Li et al., 2017), which may lead to an underestimation of SO_2 budget using satellite data in China for most recent years and a disagreement between emission and SO_2 column trend when high-stack emissions (e.g., power plants) were significantly reduced.

page 11, section Conclusion; As mentioned earlier, the language of the paper is like it all was certain but in reality there is a lot of assumptions made and the 'proof' is a mix of reports (not peer reviewed I assume), peer reviewed studies, measurements, and authors assumptions. Some discussion of uncertainty, even if in qualitative terms would be of great value. Again, the reference and discussion of impacts on the $PM_{2.5}$ trends (all these actions and plans are done for the PM). How sustainable this reduction is, a rebound likely (CO_2 in 2016 and 2017 was estimated to show revert trend).

Response:

In the revised manuscript, we use the words like "were estimated to decline" to clarify that the conclusions are made based on our bottom-up emission estimates. We also summarize the uncertainties of emission estimates in qualitative terms in Sect. 4.3.

For the $PM_{2.5}$ trends, we add a sentence in the conclusion section as "the emissions trends of $PM_{2.5}$ precursors agree well with changes in $PM_{2.5}$ compositions over China". Detailed discussions are provided in Sect. 4.3 as the reviewer suggested.

We think the reduction in China's air pollutant emissions is very unlikely to rebound for the following reason. All the reductions in emissions from 2010–2017 were driven by the objective to reduce $PM_{2.5}$ pollutions in China. The Clean Air Action implemented since 2013 has cut annual average $PM_{2.5}$ concentrations by 35% during the period of 2013–2017. For years after 2017, all cities that exceed the 35 $\mu g\ m^{-3}$ annual standard are further required to reduce annual average $PM_{2.5}$ concentrations by 18% below the 2015 level in 2020. Since the annual average limit of $PM_{2.5}$ is exceeded in many Chinese cities currently, the 2020 air quality target will continue driving down China's air pollutant emissions in the future. We clarify this in the conclusion section.

Page 22, Figure 7: I am a bit puzzled about the Figure b where For SO_2 only reduction is shown while for other species there is increase from activity driven change. Which sources cause such a change? This is unique to industry it seems, all other charts/sectors show change in the same direction and just the magnitude is different.

Response:

For the industry sector, the activity driven decrease in SO_2 emissions is caused by reduced coal use in industrial boilers. This also reduces emissions of all the other species in the industry sector. However, for other emission species, the activity increase driven by other industrial sources totally offset the effect of decreasing activities from industrial boilers. For example, the iron and steel industry drives up CO emissions; the cement industry drives up NO_x emissions; coke, iron, and steel industries drive up particulate matter emissions. This phenomenon is only observed in the industry sector, because this sector is a combination of many industrial sources in this study. The total effect of activity and pollution control on industrial emissions need to consider all the detailed sources as well as their emission shares in the industry sector.

Reference

Huo, H., Yao, Z., He, K., and Yu, X.: Fuel consumption rates of passenger cars in China: Labels versus real-world, Energy Policy, 39, 7130-7135, doi: 10.1016/j.enpol.2011.08.031, 2011.

Li, C., McLinden, C., Fioletov, V., Krotkov, N., Carn, S., Joiner, J., Streets, D., He, H., Ren, X., Li, Z., and Dickerson, R. R.: India Is Overtaking China as the World's Largest Emitter of Anthropogenic Sulfur Dioxide, Scientific Reports, 7, 14304, doi:10.1038/s41598-017-14639-8, 2017.

Shao, P., Tian, H., Sun, Y., Liu, H., Wu, B., Liu, S., Liu, X., Wu, Y., Liang, W., Wang, Y., Gao, J., Xue, Y., Bai, X., Liu, W., Lin, S., and Hu, G.: Characterizing remarkable changes of severe haze events and chemical compositions in multi-size airborne particles (PM_1, $PM_{2.5}$ and PM_{10}) from January 2013 to 2016–2017 winter in Beijing, China, Atmos. Environ., 189, 133-144, doi: 10.1016/j.atmosenv.2018.06.038, 2018.

Uno, I., He, Y., Ohara, T., Yamaji, K., Kurokawa, J. I., Katayama, M., Wang, Z., Noguchi, K., Hayashida, S., Richter, A., and Burrows, J. P.: Systematic analysis of interannual and seasonal variations of model-simulated tropospheric NO_2 in Asia and comparison with GOME-satellite data, Atmos. Chem. Phys., 7, 1671-1681, doi: 10.5194/acp-7-1671-2007, 2007.

Reviewer #2:

Comments:

The authors investigated the key trends and drivers of China's anthropogenic emissions for the period of 2010–2017 for the first time. They used a bottom-up emission inventory to quantify emissions for each source sector in each Chinese province, and then combined the estimated emissions data with the Index Decomposition Analysis approach to analyze the drivers of emission trends. The results suggest that China reduced its anthropogenic emissions by a large extent between 2010 and 2017, and emission control measures are the main drivers of this reduction, especially since 2013 when China's Clean Air Action was successfully implemented. The trends in China's emissions are evaluated with both satellite- and ground-based measurement of SO_2 and NO_2 concentrations, which confirm the certainty of the estimated emissions trends. This work is absolutely within the scope of the ACP journal. Overall, I think the paper reads well, provides valuable results, and could be published after the following issues are addressed.

Response:

We thank the reviewer #2 for the comments and our point-by-point response is given below.

1. The article makes heavy use of data sets that appear to be confidential or have restricted access, such as the technology penetration data achieved from China's Ministry of Environmental Protection (line 13, page 5). It would be helpful to other researchers if the authors describe these data a bit more clearly, such as which data are used, how these data sources are compiled, and the role these data play in the calculation of emissions in this paper.

Response:

We obtained the firm-level statistics for electric generators, cement factories, iron- and steel-making furnaces, and glass kilns from China's Ministration of Environmental Protection (MEP). These data are collected from each plant by local agencies, and then managed and verified by MEP. The information adopted in this study include pollution control technologies, penetrations, and efficiencies for different industries in each province, which are used to calibrate emission control levels (i.e., C and η in Eq. (1)) in the bottom-up inventory. We clarify this in Sect. 3.1.

2. The emissions trends estimated in this paper are built upon a variety of input data, including official statistics, government reports (not peer reviewed if I understand it correctly), and peer reviewed literatures. I understand the effort made by the authors that update emission inventories to the latest year using a mix of data sources. However, the audience may want to know the certainty of these data and how they affect the certainty of the estimated emissions trends, even if in qualitative terms would be very helpful. For example, care must be taken to confirm that targeted goals/progress from government reports may not be taken as actual emission reductions, although I believe China's emissions are decreasing fast in the last several years after reading this paper.

Response:

We add a discussion on the uncertainties of emission trend estimates in qualitative terms as the reviewer suggested. Please refer to Sect. 4.3 for more details.

3. According to the emissions results, China's emissions decreased fast since 2013 mainly due to China's Clean Air Action. I suggest the authors add a bit more description of China's Clean Air Action in the introduction part. Besides, since reducing ambient $PM_{2.5}$ pollution is the primary objective that stimulate emission control actions, the discussions on $PM_{2.5}$ concentration trends and the possible linkage to the estimated emission trends may be added in the Sect. 4.3.

Response:

We add the following sentences in the introduction part to describe China's Clean Air Action.

"The Clean Air Action is China's first five year plan (2013–2017) that radically tightened air pollution targets for particulate matter pollution reduction. The three metropolitan regions mentioned above were required to reduce $PM_{2.5}$ concentrations by 15–25% by the year 2017 compared with the 2013 levels, and all other provinces in China were required to reduce PM_{10} concentrations by 10%. The Clean Air Action launched stringent measures to achieve these air quality targets, including the adjustment of energy mix and industrial structure, reduction of air pollutant emissions, establishment of monitoring and early-warning systems for air pollution, and other supportive policies. With the successful policy implementation, China met the 2017 air pollution target set under 2013 Clean Air Action, and the annual average $PM_{2.5}$ concentrations were reduced by 28–40% from 2013–2017 in the three metropolitan regions (China, 2018)."

We add a general discussion on $PM_{2.5}$ concentration trends and the relation to the estimated emissions in the first paragraph of Sect. 4.3.

4. The authors should be more specific to what they refer in the main text. For example, in line 13 page 3, "to fulfill the air quality target", not clear what the air quality target is. In line 2 page 4, what do the "emission-intensive industries" include? In line 24 page 10, what's the definition of "Eastern China"?

Response:

The air quality targets refer to those set under 2013 Clean Air Action, which are described in detail in the introduction part now. We change the sentence to "To fulfill the air quality target set under 2013 Clean Air Action".

The emission-intensive industries mainly include iron and steel making, cement, brick, coke, glass, and chemical industries. We clarify this in the main text.

The Eastern China discussed in this paper includes the provinces of Beijing, Tianjin, Hebei, Shanxi, Shaanxi, Shandong, Henan, Hubei, Anhui, Jiangsu, Shanghai, and Zhejiang. The definition of Eastern China is given in the caption of Fig. 8.

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

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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 +16% 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.~~regional climate. These pollutants not only ~~represent~~cause local to regional environmental problems such as premature deaths and agricultural yield losses, but ~~are~~ also ~~a global problem due to global warming issues.~~have significant impact on regional climate changes in temperature and precipitation. To tackle the problems of both air pollution and regional 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 to ten times higher than the WHO's ~~acceptable standards.~~$PM_{2.5}$ guideline value of 10 μg m^{-3} (World Health Organization, 2006). 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 Clean Air Action is China's first five year plan (2013–2017) that radically tightened air pollution targets for particulate matter pollution reduction. The three metropolitan regions mentioned above were required to reduce ~~their~~$PM_{2.5}$ concentrations ~~of $PM_{2.5}$~~ by 15–25% by the year 2017 compared with ~~their~~the 2013 levels, and all other provinces in China were required to reduce ~~their~~ PM_{10} concentrations by 10%. ~~These~~The Clean Air Action launched stringent measures to achieve these air quality targets ~~have imposed more stringent clean air requirements since 2013~~, including the adjustment of energy mix and ~~finally reduced~~ industrial structure, reduction of air pollutant emissions, establishment of monitoring and early-warning systems for air pollution, and other supportive policies. With the successful policy implementation, China met the 2017 air pollution target set under 2013 Clean Air Action, and the annual average $PM_{2.5}$ concentrations were reduced by 28–40% from 2013–2017 in the three metropolitan regions (China, 2018). Space- and ground-based observations have also 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, and $PM_{2.5}$, 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 set under 2013 Clean Air Action, 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). This figure is estimated on the basis of firm-level information of pollution control devices and efficiencies,

which are collected from each plant by local agencies, and then managed and verified by Ministration of Environmental Protection of China. The power plants that comply with "ultralow emission" standards are mainly large ones at the current stage. Most of them use continuous emission monitoring systems to monitor exhaust emissions, which confirm that these plants are indeed complying with the "ultralow" emission levels.

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 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, including iron and steel making, cement, brick, coke, glass, and chemical industries. For example, the emission limits of cement plants were 800 mg m^{-3} for NO_x and 50 mg m^{-3} for particulates before 2014 (the standard GB 4915-2004), while after 2014 all cement plants were required to reach new limit values of 400 mg m^{-3} for NO_x and of 30 mg m^{-3} for particulates (the standard GB 4915-2013). For coal boilers used in industries, the emission limits were 900 mg m^{-3} for SO_2 and 80–250 mg m^{-3} for particulates before 2014 (the standard GB 13271-2001), and no limits were required for NO_x. After 2014, new coal-fired industrial boilers faced stricter limit values of 300, 300 and 50 mg m^{-3} for SO_2, NO_x and particulates (the standard GB 13271-2014), respectively. The new emission standard also tightened the limit values for existing coal-fired industrial boilers, where the "not to exceed" limits for SO_2, NO_x and particulates were 400, 400 and 80 mg m^{-3}, respectively.

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). These fuel economy data are based on laboratory tests under the European standard driving cycle, while the real-world fuel consumption rates are typically 15% higher than these tested values (Huo et al., 2011) because the European test procedure cannot reflect the real urban and highway driving conditions in China. 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 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 (MEP) 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). These data are collected from each plant by local agencies, and then managed and verified by MEP. The information adopted in this study include pollution control technologies, penetrations, and efficiencies for electric generators, cement factories, iron- and steel-making furnaces, and glass kilns in each province, which are used to calibrate emission control levels (i.e., C and η in Eq. (1)) in the bottom-up inventory. 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.

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:

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

The technology distribution factors $X_{i,j,m}$ in Eq. (1) are assembled into the row vector $\mathbf{x}$, and the relevant unabated emission factors $EF_{i,j,k,m}$ are assembled into a diagonal matrix $\mathbf{E}$. 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).

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

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 **η** 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 **η** 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.

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, NO_2, and ~~NO_2~~$PM_{2.5}$ 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 decreasedare estimated to decline 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 since 2010 (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, our estimates suggest that CO emissions decreased by 23%, whereas CO_2 emissions increased by 2%,were flat, 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. according to our calculations. In contrast, NMVOC emissions increasedare estimated to increase 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 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 increasedare estimated to increase 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, and chemical industry, which consequently drove up their total emissions. The use of solvent use for paints increased by 110% from 2010, which is attributed to the increasing demand to coat buildings, cars, and the use machinery due to the rapid increase in the area of newly built house (+52%) and the production of vehicles (+54%). The solvent for manufacturinguse in chemical productsindustry also rose at a fast rate due to the increase in production (e.g., ethylene production has growngrew by 28% since 2010).), which makes them the second largest contributor to NMVOC growth after paints. 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). TheAccording to our estimates 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 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 inare estimated to reduce their 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~~were estimated to decrease 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 based on the analysis) 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 **x**, **E**, and **η**) into sectors (~~Figs~~Fig. 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 according to our calculations, 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~~China has scrapped all the old vehicles that don't meet stringent emission standards, i.e., "yellow label" vehicles, by the end of 2017. The number of vehicles scrapped in each province are recorded by local government, and these scrapped vehicles are banned from roads and sent to wrecking yard for recycling. Consequently, 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 and implication for uncertainties

~~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 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).~~

Comparison of trends in $PM_{2.5}$ precursor emissions with satellite and ground-based $PM_{2.5}$ concentrations are presented in Fig. 8a. All data are normalized to the year 2013 because it is the only year that all data are available. Satellite-derived $PM_{2.5}$ concentrations presented a relatively flat trend during 2010 and 2013 (e.g., Fontes et al., 2017; Liang et al., 2018; Lin et al., 2018), corresponding to small variations in emissions of different precursors estimated for the same period. Satellite-based

$PM_{2.5}$ concentrations over China decreased by 18% from 2013–2015 (Lin et al., 2018), in good agreement with trend in surface $PM_{2.5}$ concentrations over 74 cities. During 2013–2017, surface $PM_{2.5}$ concentrations over 74 cites decreased by 35%, while emissions of $PM_{2.5}$ precursors over China presented various changing rates. We estimated faster decrease in SO_2 emissions than observed surface $PM_{2.5}$ concentrations, while estimated decrease rates of NO_x and NH_3 emissions were slower than observed $PM_{2.5}$ concentrations. This phenomenon was qualitatively confirmed by observed large decrease of sulfate and increased relative contribution of nitrate in $PM_{2.5}$ compositions from 2013–2017 (Shao et al. 2018). However, quantitative relationship between $PM_{2.5}$ concentrations and precursor emissions will require further studies with chemical transport modelling.

Trends in NO_x and SO_2 emissions are generally consistent with satellite- and ground-based observations during 2010–2017 (Fig. 8b and Table 2). Specifically, rapid decrease of SO_2 and NO_x emissions after 2013 are confirmed by satellite-based observations. We estimate that NO_x and SO_2 emissions in Eastern China were decreased by 21% and 59% during 2013–2017 respectively, lower than 30% and 73% decrease in OMI observed NO_2 and SO_2 columns for the same region and time period. Surface SO_2 concentrations decreased by 57% over Eastern China for the period of 2013–2017, in good agreement with estimated emission trend. On contrast, surface NO_2 concentrations only decreased by 9% for the same time, significantly lower than estimated trend in NO_x emissions.

Different trends between emissions and concentrations could be attributed to many factors. First, temporal and spatial patterns of emissions and concentrations are impacted by variations in meteorology, atmospheric transport, and chemical reactions. Interannual variabilities can result in remarkable variations in column and surface concentrations (Uno et al., 2007), which may partly explain the disagreement between changes in emissions and observations for a signal year (e.g., year 2011 in Fig. 8b). Surface observations are more sensitive to surface emissions than high-stack emissions and satellite-based column observations are more visible to high-stack emissions due to different transport patterns, in which both will contribute to the differences when comparing trends. In addition, chemical partitioning of NO_2/NO_x may also contribute to discrepancies between trends in emissions and observations (Lamsal et al., 2011, Valin et al., 2011). Taking above factors into account, inverse modeling (IM) approaches were developed to derive top-down emissions constrained by observations. Table 2 presented recently published estimates on top-down emission trends over China using IM approaches. As shown in Table 2, the discrepancies between bottom-up and top-down emission estimates are not always narrowed, indicating uncertainties from other aspects might exist.

Second, uncertainties in observations can also contribute to the discrepancies. *In-situ* observations are usually thought to be more accurate, however, surface NO_2 concentrations obtained from national monitoring network relied on chemiluminescence measurements, which can significantly overestimate NO_2 concentrations (Lamsal et al., 2010) and then contribute to discrepancies between emissions and surface observations. Satellite retrievals are subject to larger uncertainties, for instance, tropospheric SO_2 columns are quite uncertain due to difficulties in isolating anthropogenic SO_2 signals from ozone and volcanic SO_2 (Krotkov et al., 2006). Most uncertainties in satellite retrievals are systematic and cancelled when trends are compared, however, influences of aerosols on satellite NO_2 retrievals (Lin et al., 2015) may impact the reliability of NO_2 column trend due to large decrease in aerosol concentrations over the discussed period. SO_2 columns are less sensitive to small and near surface emissions (Li et al., 2017a), which may lead to an underestimation of SO_2 budget in China for most recent years and a disagreement between emission and SO_2 column trend when high-stack emissions (e.g., power plants) were significantly reduced.

Last but not least, emissions estimates are uncertain due to incomplete knowledge of underlying data (Zhao et al., 2011; Li et al., 2017c). Similar magnitudes of uncertainties are expected comparing to our previous work (e.g., Zhang et al., 2009; Lei et al., 2011; Lu et al., 2011; Li et al., 2017c) since similar methodologies and data sources are used. In general, uncertainties are smaller for species which emissions are dominant by large sources (e.g., SO_2 and NO_x) but larger for species which emissions are mainly contributed by scattered emitting sources (e.g., BC and OC). Many of uncertainties in bottom-up emissions are also systematic and may have less impacts on emission trend (Lu et al., 2011), but incompliance with regulations due to lack of inspection will lead to differences between estimated and real-world efficiencies of emission control facilities (e.g., Wang et al., 2015) and impact the validity of estimated emission trend. Specifically, the effectiveness of the measures targeting the small and scattered emitting sources (e.g., phase out small and polluted factories and eliminate small coal-fired industrial boilers) are difficult to validate, which may lead to higher uncertainty ranges in emission estimates for most recent years.

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.~~ according to our estimates. Compared to observations, the trends in NO_x and SO_2 emissions are broadly consistent with OMI satellite and ground-based measurement, and the emissions trends of $PM_{2.5}$ precursors agree well with changes in $PM_{2.5}$ compositions over China. Some differences between emissions trends and observations could be attributed to uncertainties in atmospheric measurement and emissions estimates, as well as the mismatch in their spatial-temporal patterns due to chemical processes in the atmosphere. Most of emission reductions were achieved after 2013, and the 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 mainly 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~~were estimated to increase by 11% and NH_3 emissions flattened because China lacked effective emission control measures ~~for~~on NMVOC and NH_3 in ~~its~~ current policies.

~~With decreasing emissions~~All these emissions reductions from 2010–2017 were driven by the objective to reduce $PM_{2.5}$ pollutions in China. For years after 2017, all cities that exceed the 35 μg m^{-3} annual standard are further required to reduce annual average $PM_{2.5}$ concentrations by 18% below the 2015 level in 2020. Since the annual average limit of $PM_{2.5}$ is exceeded in many Chinese cities currently, the 2020 air quality target will continue driving down China's air pollutant emissions in the future. With emissions going down, 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.~~emission reductions. China's clean air policies ~~have~~during 2013–2017 had limited effects on reducing emissions from the residential, off-road, vehicle evaporative, solvent use, and agricultural sectors~~ until the present. These~~; therefore, these sectors have significantly increased their contributions from 2010 to 2017 based on our analysis (Fig. 9~~); therefore, China needs to increase its focus on these sectors from now on. For example, the~~). The residential sector ~~accounted~~was estimated to account for 23–50% of SO_2 and particulate emissions in 2017, comparable to or even larger than the emissions ~~of~~from the power and industrial sectors. The contribution of off-road transport to NO_x emissions ~~increased~~was estimated to increase from 8% to 12% (Fig. 9b) and thus ranked as the fourth largest single sector in 2017. For road transport, evaporation emissions of NMVOC are larger than tailpipe emissions now because the tailpipe emissions were reduced significantly from 2010–2017. A wide range of solvent-using activities drove up NMVOC emissions, ~~and~~therefore 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~~large potential effects on China's 2020 air quality~~;~~, target, thus~~, more attention must be paid~~ China needs to ~~them in the future~~increase its focus on these sources from now on.

Data availability

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

Acknowledgements

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References

Boersma, K. F., Eskes, H. J., Dirksen, R. J., van der A, R. J., Veefkind, J. P., Stammes, P., Huijnen, V., Kleipool, Q. L., Sneep, M., Claas, J., Leitão, J., Richter, A., Zhou, Y., and Brunner, D.: An improved tropospheric NO_2 column retrieval algorithm for the Ozone Monitoring Instrument, Atmos. Meas. Tech., 4, 1905-1928, doi: 10.5194/amt-4-1905-2011, 2011.

China: Air quality targets set by the Action Plan have been fully realized, http://www.gov.cn/xinwen/2018-02/01/content_5262720.htm, 2018.

China State Council: Action Plan on Prevention and Control of Air Pollution, China State Council, Beijing, China, http://www.gov.cn/zwgk/2013-09/12/content_2486773.htm, 2013.

China State Council: The 13th Five-Year plan on energy saving and emissions reduction, China State Council, Beijing, China, http://www.gov.cn/zhengce/content/2017-01/05/content_5156789.htm, 2016.

de Foy, B., Lu, Z., and Streets, D. G.: Satellite NO_2 retrievals suggest China has exceeded its NO_x reduction goals from the twelfth Five-Year Plan, 6, 35912, doi: 10.1038/srep35912, 2016.

Dietzenbacher, E., and Los, B.: Structural Decomposition Techniques: Sense and Sensitivity, Economic Systems Research, 10, 307-324, doi: 10.1080/09535319800000023, 1998.

Hoekstra, R., and van den Bergh, J. C. J. M.: Comparing structural decomposition analysis and index, Energy Economics, 25, 39-64, doi: 10.1016/S0140-9883(02)00059-2, 2003.

Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N., Kurokawa, J. I., Li, M., Liu, L., Lu, Z., Moura, M. C. P., O'Rourke, P. R., and Zhang, Q.: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS), Geosci. Model Dev., 11, 369-408, doi: 10.5194/gmd-11-369-2018, 2018.

Fontes, T., Li, P., Barros, N., and Zhao, P.: Trends of $PM_{2.5}$ concentrations in China: A long term approach, Journal of Environmental Management, 196, 719-732, doi: 10.1016/j.jenvman.2017.03.074, 2017.

Huo, H., Yao, Z., He, K., and Yu, X.: Fuel consumption rates of passenger cars in China: Labels versus real-world, Energy Policy, 39, 7130-7135, doi: 10.1016/j.enpol.2011.08.031, 2011.

Jiang, Z., Worden, J. R., Worden, H., Deeter, M., Jones, D. B. A., Arellano, A. F., and Henze, D. K.: A 15-year record of CO emissions constrained by MOPITT CO observations, Atmos. Chem. Phys., 17, 4565-4583, doi: 10.5194/acp-17-4565-2017, 2017.

Koukouli, M. E., Theys, N., Ding, J., Zyrichidou, I., Mijling, B., Balis, D., and van der A, R. J.: Updated SO2 emission estimates over China using OMI/Aura observations, Atmos. Meas. Tech., 11, 1817-1832, doi: 10.5194/amt-11-1817-2018, 2018.

Krotkov, N. A., Carn, S. A., Krueger, A. J., Bhartia, P. K., and Kai, Y.: Band residual difference algorithm for retrieval of SO_2 from the aura ozone monitoring instrument (OMI), IEEE Transactions on Geoscience and Remote Sensing, 44, 1259-1266, doi: 10.1109/TGRS.2005.861932, 2006.

Krotkov, A. N., Li, C., and Leonard, P.: OMI/Aura Sulfur Dioxide (SO_2) Total Column L3 1 day Best Pixel in 0.25 degree × 0.25 degree V3, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), doi: 10.5067/Aura/OMI/DATA3008, 2015.

Krotkov, A. N., McLinden, C. A., Li, C., Lamsal, L. N., Celarier, E. A., Marchenko, S. V., Swartz, W. H., Bucsela, E. J., Joiner, J., Duncan, B. N., Boersma, K. F., Veefkind, J. P., Levelt, P. F., Fioletov, V. E., Dickerson, R. R., He, H., Lu, Z., and Streets, D. G.: Aura OMI observations of regional SO_2 and NO_2 pollution changes from 2005 to 2015, Atmos. Chem. Phys., 16, 4605-4629, doi: 10.5194/acp-16-4605-2016, 2016.

Lamsal, L. N., Martin, R. V., Padmanabhan, A., van Donkelaar, A., Zhang, Q., Sioris, C. E., Chance, K., Kurosu, T. P., and Newchurch, M. J.: Application of satellite observations for timely updates to global anthropogenic NO_x emission inventories, Geophys. Res. Lett., 38, doi: doi:10.1029/2010GL046476, 2011.

Lamsal, L. N., Martin, R. V., van Donkelaar, A., Celarier, E. A., Bucsela, E. J., Boersma, K. F., Dirksen, R., Luo, C., and Wang, Y.: Indirect validation of tropospheric nitrogen dioxide retrieved from the OMI satellite instrument: Insight into the seasonal variation of nitrogen oxides at northern midlatitudes, J. Geophys. Res. Atmos., 115, doi: doi:10.1029/2009JD013351, 2010.

Lei, Y., Zhang, Q., He, K. B., and Streets, D. G.: Primary anthropogenic aerosol emission trends for China, 1990–2005, Atmos. Chem. Phys., 11, 931-954, doi: 10.5194/acp-11-931-2011, 2011.

Li, M., Zhang, Q., Streets, D. G., He, K. B., Cheng, Y. F., Emmons, L. K., Huo, H., Kang, S. C., Lu, Z., Shao, M., Su, H., Yu, X., and Zhang, Y.: Mapping Asian anthropogenic emissions of non-methane volatile organic compounds to multiple chemical mechanisms, Atmos. Chem. Phys., 14, 5617-5638, doi: 10.5194/acp-14-5617-2014, 2014.

Li, C., McLinden, C., Fioletov, V., Krotkov, N., Carn, S., Joiner, J., Streets, D., He, H., Ren, X., Li, Z., and Dickerson, R. R.: India Is Overtaking China as the World's Largest Emitter of Anthropogenic Sulfur Dioxide, Scientific Reports, 7, 14304, doi:10.1038/s41598-017-14639-8, 2017a.

Li, M., Zhang, Q., Kurokawa, J. I., Woo, J. H., He, K., Lu, Z., Ohara, T., Song, Y., Streets, D. G., Carmichael, G. R., Cheng, Y., Hong, C., Huo, H., Jiang, X., Kang, S., Liu, F., Su, H., and Zheng, B.: MIX: a mosaic Asian anthropogenic emission inventory under the international collaboration framework of the MICS-Asia and HTAP, Atmos. Chem. Phys., 17, 935-963, doi: 10.5194/acp-17-935-2017, 2017b.

Li, M., Liu, H., Geng, G., Hong, C., Liu, F., Song, Y., Tong, D., Zheng, B., Cui, H., Man, H., Zhang, Q., and He, K.: Anthropogenic emission inventories in China: a review, National Science Review, 4, 834-866, doi: 10.1093/nsr/nwx150, 2017c.

Liang, F., Xiao, Q., Wang, Y., Lyapustin, A., Li, G., Gu, D., Pan, X., and Liu, Y.: MAIAC-based long-term spatiotemporal trends of $PM_{2.5}$ in Beijing, China, Sci. Total Environ., 616-617, 1589-1598, doi: 10.1016/j.scitotenv.2017.10.155, 2018.

Lin, C. Q., Liu, G., Lau, A. K. H., Li, Y., Li, C. C., Fung, J. C. H., and Lao, X. Q.: High-resolution satellite remote sensing of provincial $PM_{2.5}$ trends in China from 2001 to 2015, Atmos. Environ., 180, 110-116, doi: 10.1016/j.atmosenv.2018.02.045, 2018.

Lin, J. T., Liu, M. Y., Xin, J. Y., Boersma, K. F., Spurr, R., Martin, R., and Zhang, Q.: Influence of aerosols and surface reflectance on satellite NO_2 retrieval: seasonal and spatial characteristics and implications for NO_x emission constraints, Atmos. Chem. Phys., 15, 11217-11241, doi: 10.5194/acp-15-11217-2015, 2015.

Liu, F., Zhang, Q., Tong, D., Zheng, B., Li, M., Huo, H., and He, K. B.: High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010, Atmos. Chem. Phys., 15, 13299-13317, doi: 10.5194/acp-15-13299-2015, 2015.

Liu, F., Zhang, Q., van der A, R. J., Zheng, B., Tong, D., Yan, L., Zheng, Y. X., and He, K. B.: Recent reduction in NO_x emissions over China: synthesis of satellite observations and emission inventories, Environ. Res. Lett., 11, 114002, 2016.

Liu, Z., Guan, D., Wei, W., Davis, S. J., Ciais, P., Bai, J., Peng, S., Zhang, Q., Hubacek, K., Marland, G., Andres, R. J., Crawford-Brown, D., Lin, J., Zhao, H., Hong, C., Boden, T. A., Feng, K., Peters, G. P., Xi, F., Liu, J., Li, Y., Zhao, Y., Zeng, N., and He, K.: Reduced carbon emission estimates from fossil fuel combustion and cement production in China, Nature, 524, 335-338, doi: 10.1038/nature14677, 2015.

Lu, Z., Streets, D. G., Zhang, Q., Wang, S., Carmichael, G. R., Cheng, Y. F., Wei, C., Chin, M., Diehl, T., and Tan, Q.: Sulfur dioxide emissions in China and sulfur trends in East Asia since 2000, Atmos. Chem. Phys., 10, 6311-6331, doi: 10.5194/acp-10-6311-2010, 2010.

Lu, Z., Zhang, Q., and Streets, D. G.: Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996–2010, Atmos. Chem. Phys., 11, 9839-9864, doi: 10.5194/acp-11-9839-2011, 2011.

Miyazaki, K., Eskes, H., Sudo, K., Boersma, K. F., Bowman, K., and Kanaya, Y.: Decadal changes in global surface NO_x emissions from multi-constituent satellite data assimilation, Atmos. Chem. Phys., 17, 807-837, doi: 10.5194/acp-17-807-2017, 2017.

National Bureau of Statistics: China Energy Statistical Yearbook 2017, China Statistics Press, Beijing, China, 2018a.

National Bureau of Statistics: Statistical Communiqué of the People's Republic of China on the 2017 National Economic and Social Development, http://www.stats.gov.cn/tjsj/zxfb/201802/t20180228_1585631.html, 2018b.

National Bureau of Statistics: China Statistical Yearbook 2017, China Statistics Press, Beijing, China, 2018c.

National Energy Administration: Statistical data of Chinese electric power industry 2017, http://www.nea.gov.cn/2018-01/22/c_136914154.htm, 2018.

Qi, J., Zheng, B., Li, M., Yu, F., Chen, C., Liu, F., Zhou, X., Yuan, J., Zhang, Q., and He, K.: A high-resolution air pollutants emission inventory in 2013 for the Beijing-Tianjin-Hebei region, China, Atmos. Environ., 170, 156-168, doi: 10.1016/j.atmosenv.2017.09.039, 2017.

Shao, P., Tian, H., Sun, Y., Liu, H., Wu, B., Liu, S., Liu, X., Wu, Y., Liang, W., Wang, Y., Gao, J., Xue, Y., Bai, X., Liu, W., Lin, S., and Hu, G.: Characterizing remarkable changes of severe haze events and chemical compositions in multi-size airborne particles (PM_1, $PM_{2.5}$ and PM_{10}) from January 2013 to 2016–2017 winter in Beijing, China, Atmos. Environ., 189, 133-144, doi: 10.1016/j.atmosenv.2018.06.038, 2018.

Streets, D. G., Zhang, Q., Wang, L., He, K., Hao, J., Wu, Y., Tang, Y., and Carmichael, G. R.: Revisiting China's CO emissions after the Transport and Chemical Evolution over the Pacific (TRACE-P) mission: Synthesis of inventories, atmospheric modeling, and observations, J. Geophys. Res. Atmos., 111, doi:10.1029/2006JD007118, 2006.

van der A, R. J., Mijling, B., Ding, J., Koukouli, M. E., Liu, F., Li, Q., Mao, H., and Theys, N.: Cleaning up the air: effectiveness of air quality policy for SO_2 and NO_x emissions in China, Atmos. Chem. Phys., 17, 1775-1789, doi: 10.5194/acp-17-1775-2017, 2017.

Uno, I., He, Y., Ohara, T., Yamaji, K., Kurokawa, J. I., Katayama, M., Wang, Z., Noguchi, K., Hayashida, S., Richter, A., and Burrows, J. P.: Systematic analysis of interannual and seasonal variations of model-simulated tropospheric NO_2 in Asia and comparison with GOME-satellite data, Atmos. Chem. Phys., 7, 1671-1681, doi: 10.5194/acp-7-1671-2007, 2007.

Valin, L. C., Russell, A. R., Hudman, R. C., and Cohen, R. C.: Effects of model resolution on the interpretation of satellite NO_2 observations, Atmos. Chem. Phys., 11, 11647-11655, doi: 10.5194/acp-11-11647-2011, 2011.

Wang, S., Zhang, Q., Martin, R., Philip, S., Liu, F., Li, M., Jiang, X., and He, K.: Satellite measurements oversee China's sulfur dioxide emission reductions from coal-fired power plants, Environ. Res. Lett., 10, 114015, 2015.

Warner, J. X., Dickerson, R. R., Wei, Z., Strow, L. L., Wang, Y., and Liang, Q.: Increased atmospheric ammonia over the world's major agricultural areas detected from space, Geophys. Res. Lett., 44, 2875-2884, doi: 10.1002/2016GL072305, 2017.

World Health Organization: WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, http://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf;jsessionid=2316300A203942FCECC2E260E5EB9A14?sequence=1, 2006.

Zhang, J., Reid, J. S., Alfaro-Contreras, R., and Xian, P.: Has China been exporting less particulate air pollution over the past decade?, Geophys. Res. Lett., 44, 2941-2948, doi: 10.1002/2017GL072617, 2017.

Zhang, Q., Streets, D. G., He, K., Wang, Y., Richter, A., Burrows, J. P., Uno, I., Jang, C. J., Chen, D., Yao, Z., and Lei, Y.: NO_x emission trends for China, 1995–2004: The view from the ground and the view from space, J. Geophys. Res. Atmos., 112, 1-18, doi: 10.1029/2007JD008684, 2007.

Zhang, Q., Streets, D. G., Carmichael, G. R., He, K. B., Huo, H., Kannari, A., Klimont, Z., Park, I. S., Reddy, S., Fu, J. S., Chen, D., Duan, L., Lei, Y., Wang, L. T., and Yao, Z. L.: Asian emissions in 2006 for the NASA INTEX-B mission, Atmos. Chem. Phys., 9, 5131-5153, doi: 10.5194/acp-9-5131-2009, 2009.

Zhang, Q., He, K., and Huo, H.: Cleaning China's air, Nature, 484, 161, doi: 10.1038/484161a, 2012.

Zhao, B., Jiang, J. H., Gu, Y., Diner, D., Worden, J., Liou, K. N., Su, H., Xing, J., Garay, M., and Huang, L.: Decadal-scale trends in regional aerosol particle properties and their linkage to emission changes, Environ. Res. Lett., 12, 054021, doi: 10.1088/1748-9326/aa6cb2, 2017.

Zhao, Y., Nielsen, C. P., Lei, Y., McElroy, M. B., and Hao, J.: Quantifying the uncertainties of a bottom-up emission inventory of anthropogenic atmospheric pollutants in China, Atmos. Chem. Phys., 11, 2295-2308, doi: 10.5194/acp-11-2295-2011, 2011.

Zheng, B., Huo, H., Zhang, Q., Yao, Z. L., Wang, X. T., Yang, X. F., Liu, H., and He, K. B.: High-resolution mapping of vehicle emissions in China in 2008, Atmos. Chem. Phys., 14, 9787-9805, doi: 10.5194/acp-14-9787-2014, 2014.

Zheng, B., Zhang, Q., Tong, D., Chen, C., Hong, C., Li, M., Geng, G., Lei, Y., Huo, H., and He, K.: Resolution dependence of uncertainties in gridded emission inventories: a case study in Hebei, China, Atmos. Chem. Phys., 17, 921-933, doi: 10.5194/acp-17-921-2017, 2017.

Zheng, B., Chevallier, F., Ciais, P., Yin, Y., Deeter, M., Worden, H., Wang, Y. L., Zhang, Q., and He, K. B.: Rapid decline in carbon monoxide emissions and export from East Asia between years 2005 and 2016, Environ. Res. Lett., 13, 044007, doi: 10.1088/1748-9326/aab2b3, 2018.

<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="11">Industry</td><td>Flat glass</td><td>GB 9078-1996</td><td colspan="7">GB 26453-2011</td></tr>
<tr><td>Sinter</td><td colspan="2">GB 9078-1996</td><td colspan="6">GB 28662-2012</td></tr>
<tr><td>Coking</td><td colspan="2">GB 16171-1996</td><td colspan="6">GB 16171-2012</td></tr>
<tr><td>Iron</td><td colspan="2">GB 9078-1996</td><td colspan="6">GB 28663-2012</td></tr>
<tr><td>Steel making</td><td colspan="2">GB 9078-1996</td><td colspan="6">GB 28664-2012</td></tr>
<tr><td>Steel rolling</td><td colspan="2">GB 9078-1996</td><td colspan="6">GB 28665-2012</td></tr>
<tr><td>Electronic glass</td><td colspan="3">GB 9078-1996</td><td colspan="5">GB 29495-2013</td></tr>
<tr><td>Brick</td><td colspan="4">GB 9078-1996</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.

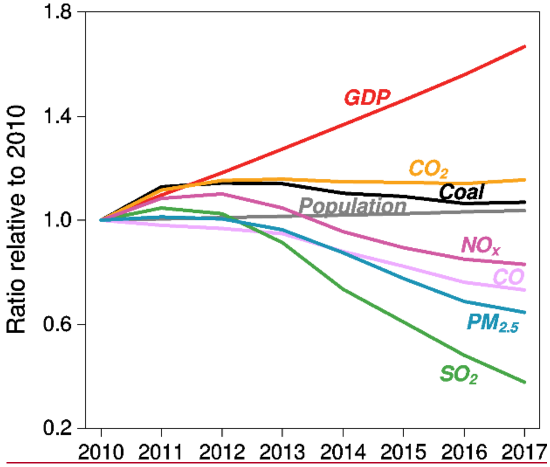

Figure 2. Emission trends and underlying social and economic factors. The coal usage are achieved from Chinese Energy Statistics (National Bureau of Statistics, 2018a, 2018b). The GDP and population data come from National Bureau of Statistics (2018b, 2018c). Data are normalized by dividing the values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

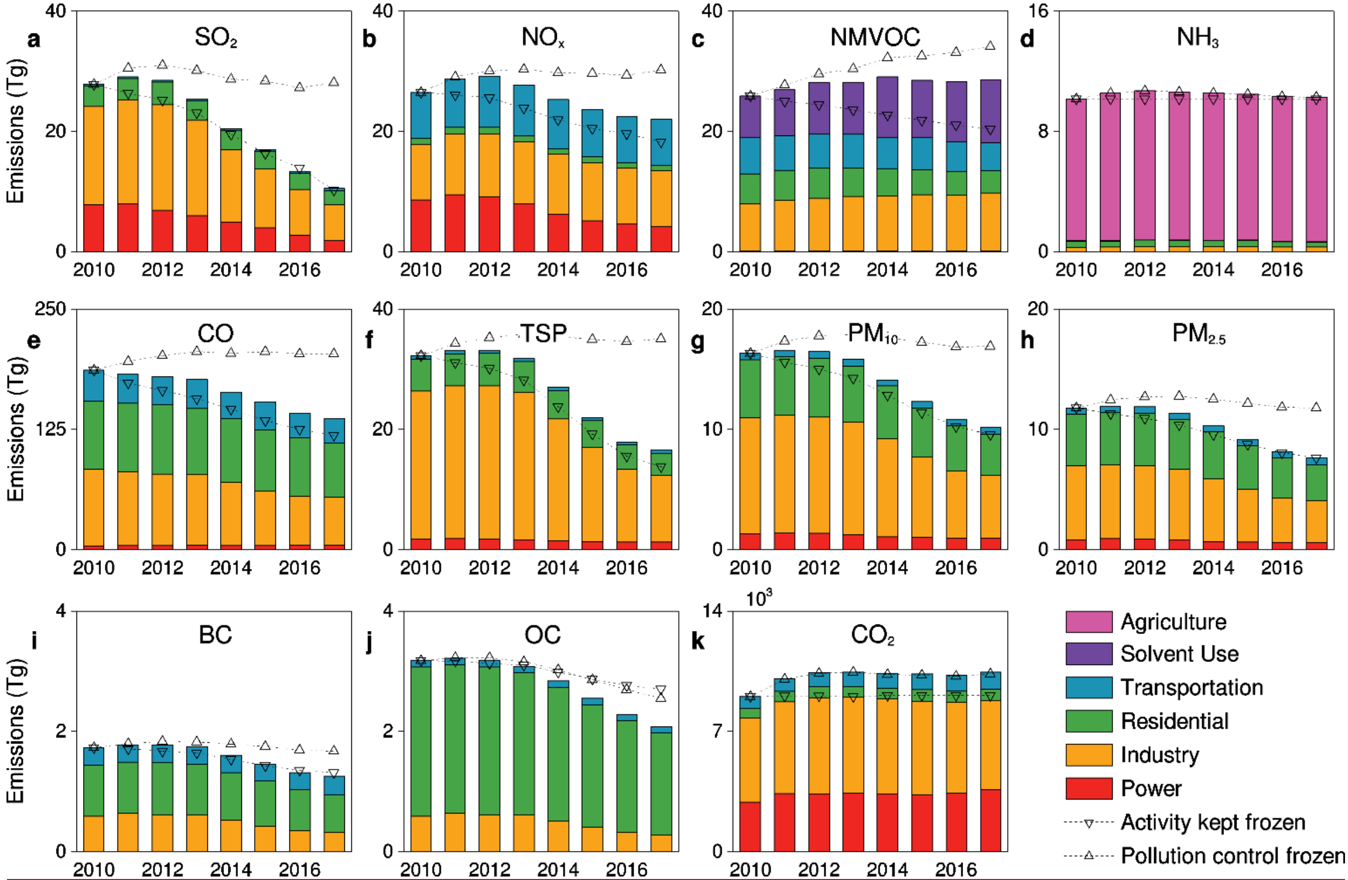

Figure 3. China's anthropogenic emissions by sector and year. The species plotted here include (a) SO_2, (b) NO_x, (c) NMVOC, (d) NH_3, (e) CO, (f) TSP, (g) PM_{10}, (h) $PM_{2.5}$, (i) BC, (j) OC, and (k) CO_2. China emissions are divided into six source sectors (stacked column chart): power, industry, 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.

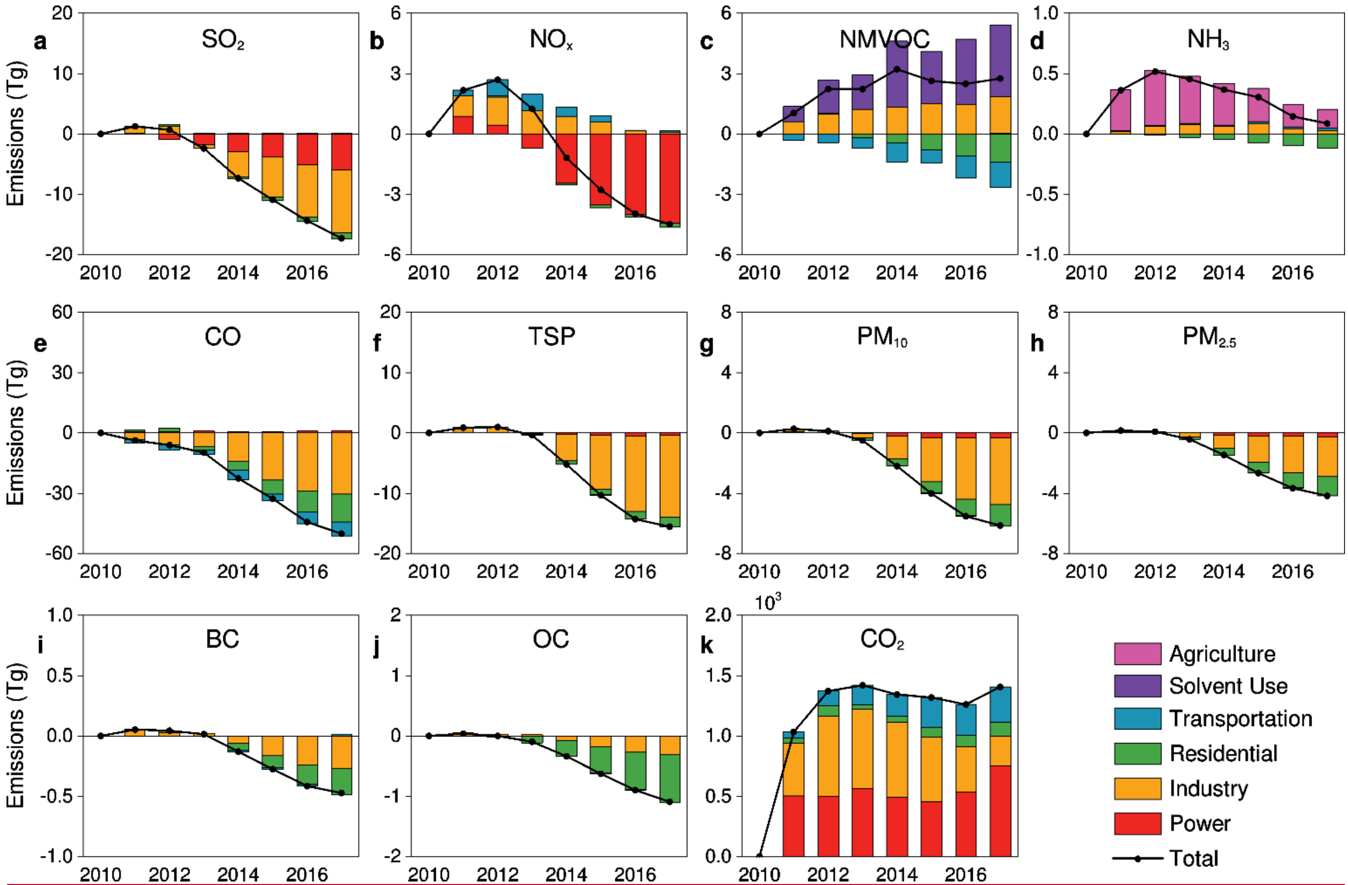

Figure 4. Changes in China's emissions by sector and year. The species plotted here include (a) SO_2, (b) NO_x, (c) NMVOC, (d) NH_3, (e) CO, (f) TSP, (g) PM_{10}, (h) $PM_{2.5}$, (i) BC, (j) OC, and (k) CO_2. The 2010 emissions are subtracted from the emission data for each year to represent the additional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

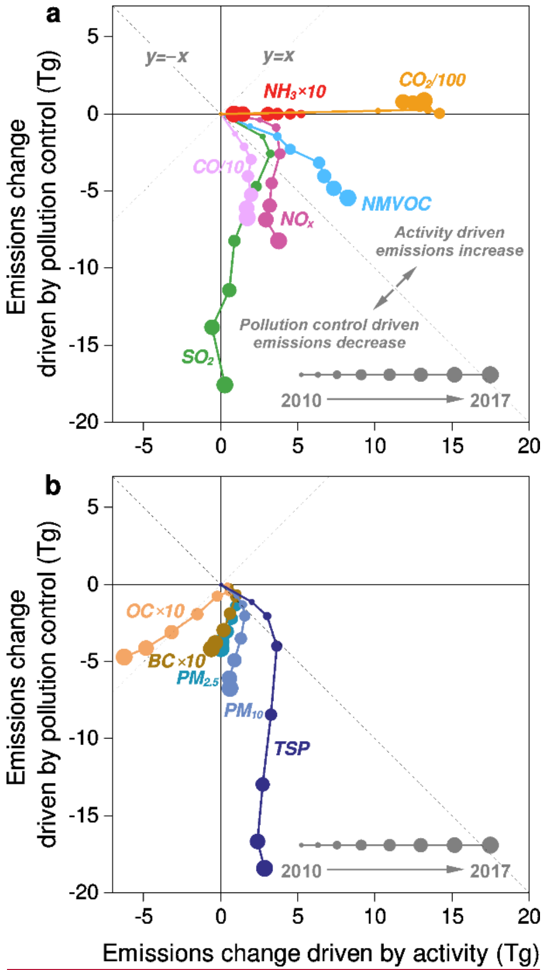

Figure 5. China's emission pathways from 2010–2017. Gaseous pollutants are plotted in (a), and particles are plotted in (b). For each pollutant, the years (circle) are plotted according to the emission changes caused by activity (*A* in Eq. (2), x-axis) and pollution control (the sum of **x**, **E** 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.

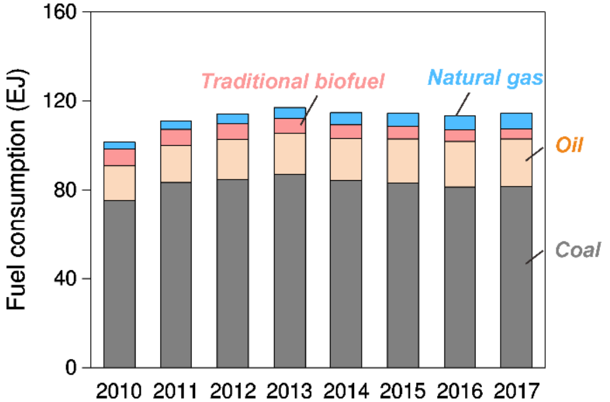

Figure 6. Energy consumption of hydrocarbon fuels from 2010 to 2017. Coal includes all coal-based fuels, and oil includes all oil-based fuels. Traditional biofuel includes crop residual and wood.

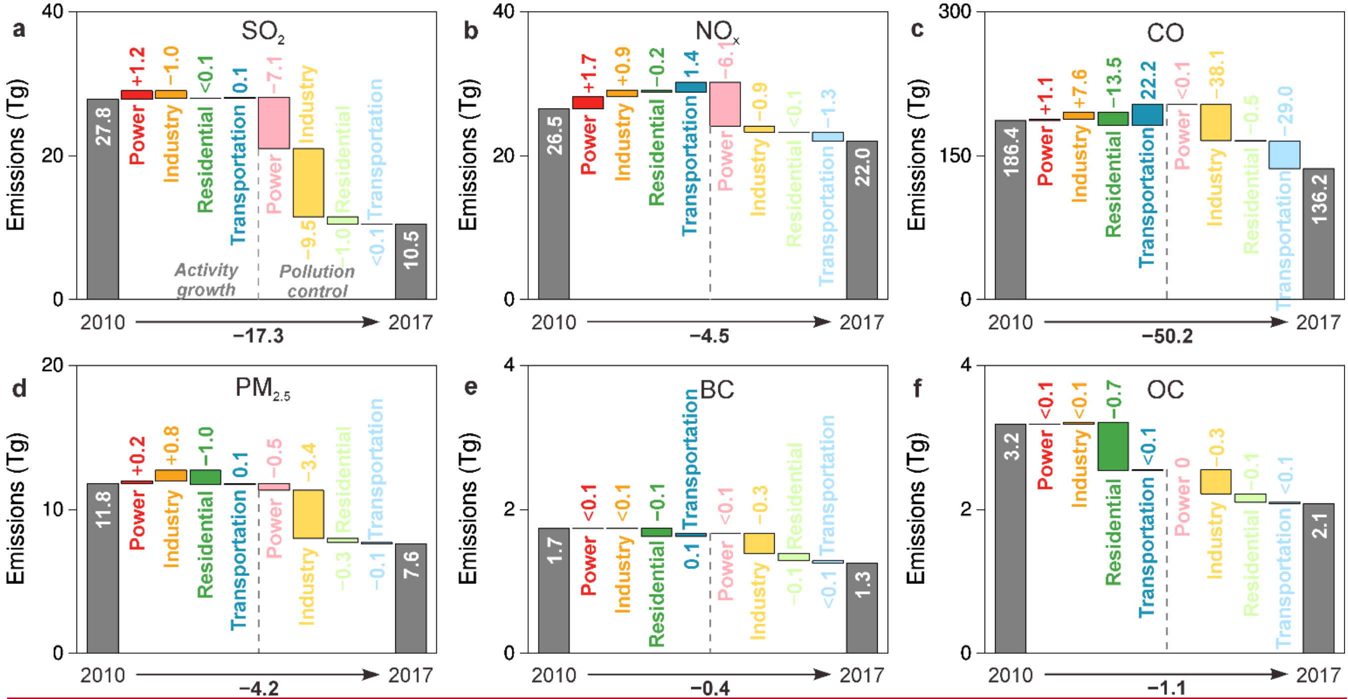

Figure 7. Drivers of emission changes for different ~~source sectors.~~emission species. The ~~sectors~~species plotted here include (a) ~~power~~SO_2, (b) ~~industry~~NO_x, (c) ~~residential~~CO, (d) $PM_{2.5}$, (e) BC, and (~~d) transportation.~~f) OC. For each ~~sector~~pollutant, the changes in emissions from 2010 to 2017 (bar) are ~~plotted according to air pollutants (x-axis) and the changes in emissions driven by~~ decomposed into drivers of activity growth (*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).~~(2)) by source sector.

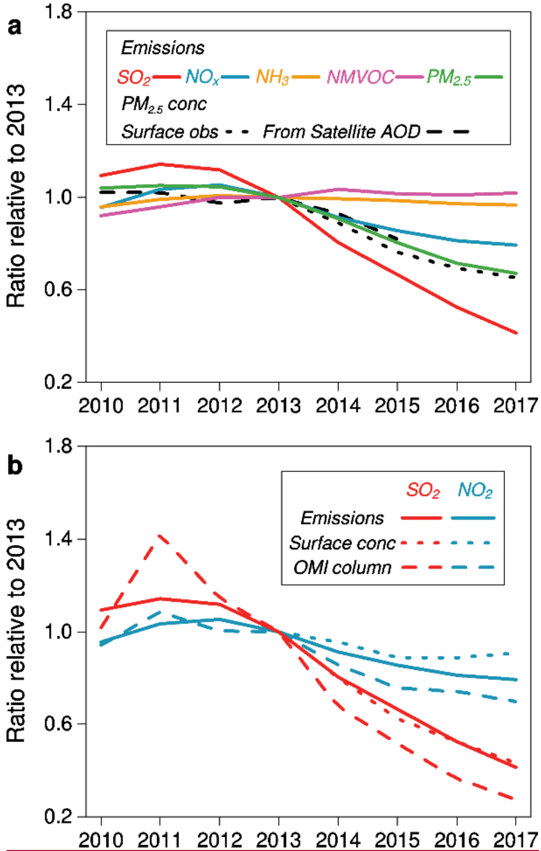

Figure 8. Emission trends compared with ~~OMI~~satellite- and ground-based observations. The satellite-retrieved $PM_{2.5}$ concentrations (black, dashed curve in a) (Lin et al., 2018) are compared with emission trends of $PM_{2.5}$ precursors in a. The 2010–2017 trends in SO_2 (red, solid curve in ~~a) 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~~OMI SO_2 (red, dashed curve in b) and NO_2 (blue, dashed curve in b~~), respectively.~~) tropospheric columns for Eastern China, respectively. The Eastern China here includes the provinces of Beijing, Tianjin, Hebei, Shanxi, Shaanxi, Shandong, Henan, Hubei, Anhui, Jiangsu, Shanghai, and Zhejiang. Besides, the 2013–2017 trends in ground-based observations of SO_2 (red, dotted curve in b), NO_2 (blue, dotted curve in b), and $PM_{2.5}$ (black, dotted curve in a) are also presented.

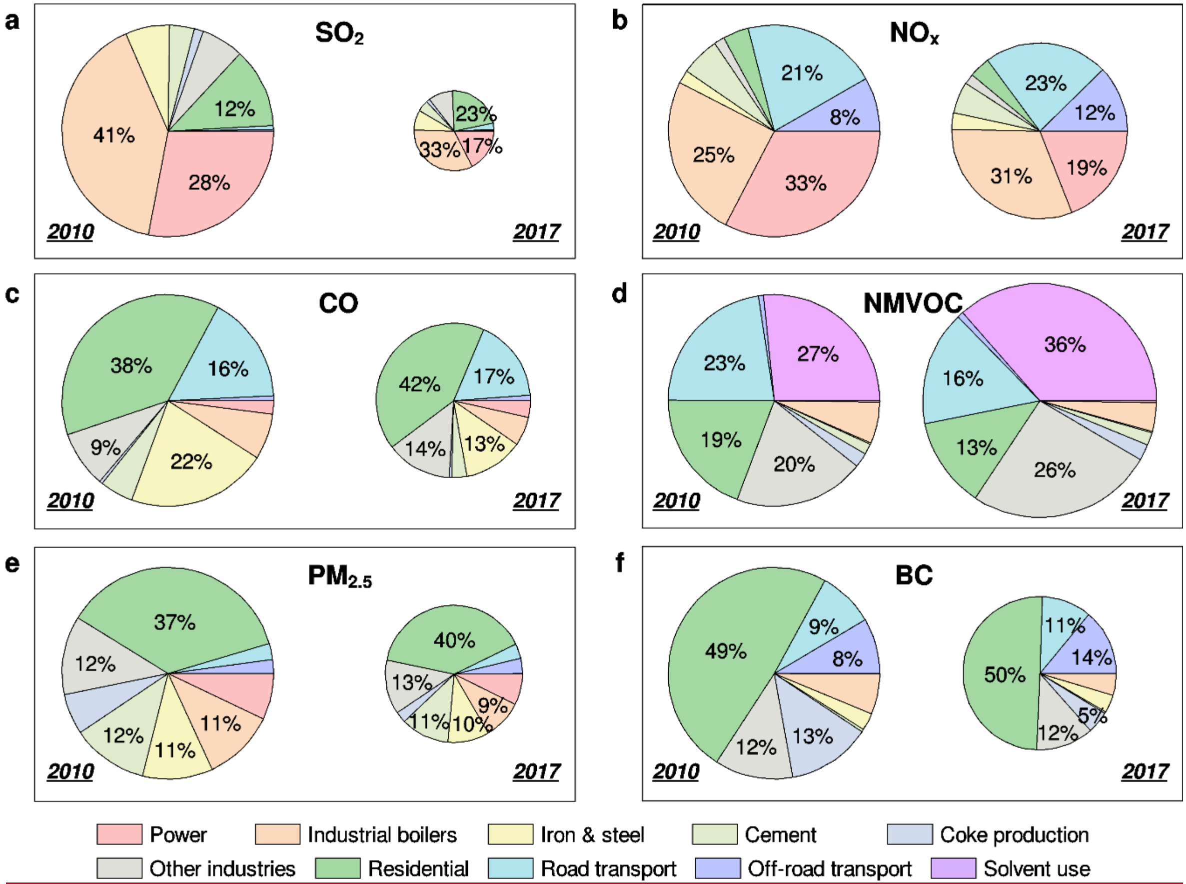

Figure 9: Changes in emission percentages across source sectors from 2010 to 2017. The species plotted here include (a) SO_2, (b) NO_x, (c) CO, (d) NMVOC, (e) $PM_{2.5}$, and (f) BC. For each pollutant, the relative change in the radius of the pie chart from 2010 to 2017 is proportional to the change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

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

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	3619.2
Industry	6.0	9.2	9.7	0.3	49.2	11.1	5.2	3.5	0.3	0.3	5161.0
Residential	2.4	0.8	3.6	0.3	57.0	3.7	3.4	3.0	0.6	1.7	676.5
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	10434.3
(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%	0%
(2017−2010)/2010	−62%	−17%	11%	1%	−27%	−48%	−38%	−35%	−27%	−35%	16%

[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.

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)	SAT	OMI SO_2 columns	China	2010–2016	−68	−52
	Li et al. (2017a)	IM	SO_2 emissions inferred from OMI SO_2 columns	China	2010–2016	−71	−52
	Koukouli et al. (2018)	IM	SO_2 emissions inferred from OMI SO_2 columns	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 inferred from OMI NO_2 columns	E China	2010–2015	−8	−14
	Miyazaki et al. (2017)	IM	NO_x emissions inferred from OMI NO_2 columns	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 inferred from MOPITT CO columns	E China	2010–2015	−13~−9	−18
	Zheng et al. (2018)	IM	CO emissions inferred from MOPITT CO columns	China	2010–2016	−25	−24

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