

Response to referee report #2

We thank Referee #2 for the valuable comments. Below we give a point-to-point response to comments by referee. The referee's comments are given in italic font, while our response is given in bold font.

The authors present a study of temporal trends of NO₂ and SO₂ derived from satellite observations over China, and relate them directly to changes in fossil fuel consumption in order to investigate the effectiveness of environmental regulations. While the former has been done in several studies before, the latter is to my knowledge new and provides an interesting approach. The study thus matches the scope of ACP and should generally be published.

However, the provided material is rather sparse (in particular as the introduction let the reader expect to see an analysis on provincial level, which is not given), and the results for NO_x are not convincing; the authors try to interpret some local maxima by some reason, but I see no consistent explanation for the whole, rather complex, temporal pattern.

Thus, the study needs major revisions, in particular for NO_x, providing additional information which either substantiates the discussion of trends or let the authors be more cautious with their statement about NO_x concentrations being 30% higher without regulations.

The temporal patterns in NO_x emissions can be explained by the (lack of) regulations on NO_x emissions, a shift in fuel consumption patterns and other economic factors. We hope to have explained the trends and our conclusions better in the revised version of our paper by adding more discussion on the results. To support our conclusions and analysis we have added in the revised version the provincial data for SO₂ concentrations and NO_x emissions per year and province. In order to clarify our findings we have revised the Figures of the time series by adding the provincial time series of the 10 most emitting provinces. More details about our revisions follow below.

Major concerns:

- Provincial levels The authors point out that it is great to have improved NO₂ and SO₂ datasets on high spatial resolution, which allow the analysis of time series on provincial level. Thus, the authors should indeed investigate the trends of SO₂, NO_x, fossil fuel, and ratios on provincial levels, which probably will provide valuable further information and help to understand/assess the NO_x-per-fuel trend (see below).

The NO_x and SO₂ datasets are indeed analysed on a provincial level. To summarize our findings we decided not to show the individual time series for 30 provinces, but instead show an average and range of the timeline for the 10 most polluted provinces. Individual time series have now been added in tables for SO₂ and NO_x with the concentration and emissions per year and per provinces. In the text we elaborated more on the provincial time series.

The fuel consumption per province was not publicly available at the time of submitting our paper. Only recently the provincial data became available for most provinces, although we have no indication of the uncertainty of these numbers, especially for the smallest provinces. The ratio per province will combine the uncertainties on these coal/oil consumption numbers with the errors in the satellite data. This makes it difficult to draw any conclusions out of these ratios and therefore we have decided to ignore the provincial fuel numbers in this study.

On the other hand, we found evidence in the papers of Guan et al. (2012) and Hong et al. (2016) that the sum of the coal consumption of all provinces is more accurate than the number provided for the whole of China, that is why we have updated Figure 5 and 6 with the total coal consumption of the provinces, which only slightly changes the results. For oil we have not enough provincial data to do the same.

Guan, D., Z. Liu, Y. Geng, S. Lindner and K. Hubacek, The gigatonne gap in China's carbon dioxide inventories, *Nature Climate Change*, 2, 672–675, (2012), doi:10.1038/nclimate1560

Hong, C., Zhang, Q., He, K., Guan, D., Li, M., Liu, F., and Zheng, B.: Variations of China's emission estimates response to uncertainties in energy statistics, *Atmos. Chem. Phys. Discuss.*, doi:10.5194/acp-2016-459, in review, 2016.

- Annual vs. semi-annual means: For SO₂, only April-September is considered "due to a lower accuracy at higher latitudes" (3.2) For NO₂, information on the kind of averaging is missing in 3.3, but later it is stated that total annual emissions are used (3.4). Why? The lower accuracy and snow/ice argument holds as well for NO₂. As the trends for both SO₂ and NO₂ are compared to fossil fuel and to each other, the period for calculating means has to be consistent. In any case, the authors should also provide the "winter"-trend for SO₂, despite the lower accuracy. Is it similar (with higher noise) or significantly different from Fig. 3?

It is true that both NO₂ and SO₂ are irregularly and sparsely sampled by the satellite at high latitudes in wintertime. This lowers the accuracy and potentially introduces biases when averages are calculated for these periods based on the available satellite measurements. The SO₂ analysis in this paper depends on such averages. NO_x emissions, however, are derived using an inversion algorithm insensitive to data gaps.

. The SO₂ data from OMI is worse in winter than in summer, but the annual data is good enough and not significantly different from Figure 3. The reason we switched to summer means is that the SCIAMACHY SO₂ observations are very scarce in winter, since in the most optimal situation SCIAMACHY has global coverage only once every 6 days. On top of that the SCIAMACHY data is more noisy due to the lower spatial resolution. To keep consistency for all SO₂ data we had done all analysis for summer means. However, triggered by and based on the remarks of the reviewer about consistency, the authors came to the conclusion that it is better to use annual averages for both OMI products, since this is the main focus of our study and these data are compared to annual coal/oil consumptions.

For SCIAMACHY and GOME-2 we still use summer values. If we switch to annual means the GOME-2 line does not change a lot, but for SCIAMACHY the changes are much larger, although the

decreasing trend clearly remains. For SCIAMACHY there is practically no data above 45 degree North and in other regions the number of data point is still scarce due to the global coverage once every 6 days. This makes the SCIAMACHY data very sensitive to weather effects.

We have adapted the text accordingly in section 3.2 and 3.3 and made new Figures 3 and 6.

- NOx regulations Almost no information is provided about the concrete NOx regulations. Please discuss the different possibilities in general, and the taken measures in detail, for reducing NOx over China, and provide a table similar as for SO2. From what I learned from the media, there were different measures taken during the Olympic games, like shutting off power plants nearby and building new ones more remotely (which would change the local, but not the total trends, underlining the need for investigations on provincial levels), or reduction of traffic (which would affect the NOx, but not the NOx per fuel). These (and other) different measures and their effect on NOx vs. NOx per fuel trends have to be discussed.

The measures mentioned by the reviewer for the Olympic Games and other events like World Expo, Youth Olympic Games, EPAC meeting, etc. are mostly of a temporary nature as shown by Mijling et al. (2009). They showed that since most measures were cancelled after the Olympic Games the NO2 levels were back to normal in a couple months.

There have been less permanent regulations for NOx emissions (besides traffic emission regulations) than for SO2, which had for some time a higher priority in China. That is why we have mentioned the NOx regulations in the text, but not made a table for these regulations. However, in the revised version we added a table for the NOx regulations and added some discussion on the traffic regulations and events.

Please note that that we relate NOx emissions to Standard Coal Equivalents (SCE). The reduction of traffic will reduce the NOx emissions but also the NOx per fuel (i.e. NOx per SCE), since NOx is emitted by two different source sectors: (1) traffic and (2) industry including energy production. Of those two source sectors traffic has a higher emission factor (i.e. NO2 per fuel) (see Zhao et al., 2013), thus a shift in source sectors result in different NOx per fuel values. Note that for SO2 this is no issue. To explain this better we have adapted the text (see the next review item).

Zhao, B., Wang, S. X., Liu, H., Xu, J. Y., Fu, K., Klimont, Z., Hao, J. M., He, K. B., Cofala, J., and Amann, M.: NOx emissions in China: historical trends and future perspectives, *Atmos. Chem. Phys.*, **13**, 9869-9897, doi:10.5194/acp-13-9869-2013, 2013.

- NOx per fossil fuel While the SO2 per fuel significantly decreases over the years, in accordance to regulations, the situation is less clear for NOx. The authors state that already 2008 the regulations worked out (explaining the 2009 minimum). But why is NOx per fuel increasing again (by 20%!) in the following years? Have the measures been cancelled? The attempt to explain Fig. 6 by shipping is pure speculation, as it is not supported by any data. The conclusion that NO2 would be 30% higher today without the measures taken is not convincing unless the decline in 2015 compared to the high plateau 2011-2014 is explained; or were all measures concerning NOx just taken in 2015? In any case,

the 30% is overestimated as it compares the minimum to the maximum of the timeseries, completely ignoring statistical fluctuations.

Important for NO_x emissions is the growth of the transport sector in China. In the last 10 years the amount of freight transport, expressed in tonnes*km, is approximately doubling every 6 years according to the official statistical information from NBSC (2016). This means that the transport sector is faster growing than the industrial/energy sector, resulting in a gradual shift in the relative shares of the source sectors, which results in gradually higher NO_x per fuel in time because of the higher emission factor of traffic (see Zhao et al., 2013). Exception of this gradual growth is the year 2009 because of the following reasons:

- The global economic crisis affected especially the transport sector, which led to a shift in source sector and a reduction of NO_x per fossil fuel. See De Ruyter de Wildt et al. (2012)
- The global economic crisis also led to the practice of slow steaming for international ship transport. See Faber et al. (2012) and Boersma et al. (2015).

This explanation has been added to the text. The text has been changed to:

“The year 2009 coincides with the global economic crisis when there was less export of goods from China. This affected especially the transport sector, mostly transport over water, as shown in De Ruyter de Wildt et al. (2012). Faber et al. (2012) and Boersma et al. (2015) showed that the economic crisis also resulted in a significant reduction of the average vessel speed to save fuel used by ship transport. This caused not only a shift in source sectors but in general led to lower NO_x per fuel values. This explains the dip in pollution per fuel unit in 2009. After 2012 the gradual increase of NO_x per fuel (as a result of the strongly growing transport sector) slowly stops, and the year 2015 shows a sharp decline in NO_x per fossil fuels unit. This can be directly related to the rapidly growing installation of Selective Catalytic Reduction (SCR) equipment at power plants since 2012 and new emission standards for cars as shown by Liu et al. (2016). “

Boersma, K.F., G.C.M. Vinken, J. Tournadre, Ships going slow in reducing their NO_x emissions: changes in 2005–2012 ship exhaust inferred from satellite measurements over Europe, Environ. Res. Letters, 10, 7, doi.10.1088/1748-9326/10/7/074007, 2015

De Ruyter de Wildt, M., H. Eskes, K. F. Boersma, The global economic cycle and satellite-derived NO₂ trends over shipping lanes, Geophys. Res. Letters, doi:10.1029/2011GL049541, 2012

Faber J, Nelissen D, Hon G, Wang H and Tsimplis M, Regulated slow steaming in maritime transport—an assessment of options, costs and benefits CE Delft (The Netherlands: Delft) (www.cedelft.eu/publicatie/regulated_slow_steaming_in_maritime_transport/1224) p 117 , 2012

The conclusion of a reduction of NO_x of 30% as a result of air quality regulations is based on the following:

- Without any air quality regulations we expect a gradual growth in NO_x per fossil fuel as a result of the relatively faster growing transport sector that has a higher emission factor. The growth stopped in the year 2012 as a result of the mandatory installation of Selective Catalytic Reduction

(SCR) equipment at power plants since 2012 and new emission standards for cars (see Table 2). When comparing the year 2015 with the 2012 level we calculate that NO_x would be at least (assuming no growth after 2012) of 25% higher without air quality measures. This is different from the earlier 30% because of the new coal numbers we are using in the revised version of the paper. We claim at least 25 % because in this calculation we don't account for the further growth of the transport sector after 2012, while in fact the fast growth of transport still continued.

Minor comments:

Page 1 Line 13: What does "spatially consistent" mean?

We mean that they have about the same quality around the world, but since that is not entirely true, we changed this to "global".

Page 1 Line 25: The factor of 3 for SO₂ is different from the statement in 3.4, and not supported by the presented data.

We changed the text in both cases to "about 2.5 times higher". In 2015 the normalized emission factor is 0.4 compared to around 1 in the period 2003-2007.

Page 1 Line 31: "concentrations" should be "column densities"

We have made this correction.

Page 2 Line 11: Please provide the full name of "He K."

We included the full name Kebin He.

Page 3 Line 2: Add a reference to Liu et al., 2016: <http://www.atmos-chem-phys.net/16/5283/2016/>

We agree and added the reference.

Page 3 Line 12: Please provide some information how and how far the new retrieval improves the quality of SO₂.

We have added that the new retrieval algorithm "improves the accuracy of the SO₂ data for OMI with a factor 2"

Page 5 Line 15: NO₂ changes during the Olympic games (or during the Shanghai Expo) have been discussed before; please add references.

We have added a reference to Mijling et al. (2009), who discuss the effect of the Olympic Games on NO_x.

Page 6 Line 25: "by definition not sensitive": This is a too strong statement which only holds under the assumption that CHIMERE is doing everything right within the DESCO algorithm.

We changed "by definition" into "in general".

Page 7 Line 6: There is no "Fig. 5b".

We removed the reference.