Responses to Anonymous Referee #1:

This manuscript presents a new methodology to look at the emissions base from the consumer perspective. This will help ascertain the footprint of various pollutants in the cities and the regions, similar to the carbon footprint.

Response: We appreciate the insightful and constructive comments from referee #1. We deal with individual comments as below.

When the topic of air pollution is at the center, is it important to look at the emission rates from the production perspective or the consumption perspective? At the end of the day, while the products are manufactured and exported to various provinces or inter nationally, the emissions are not. Their impact is still local and that is not transported.

This work, while presents a new perspective, the problem of air pollution is still where the emissions are and not where the consumers are. While the message is not to stop manufacturing for trade, this is still at the center of the discussion - how much of these emissions are resulting from producing products not for use locally? One could extend the current analysis, from the production perspective to show the footprint of emissions from local consumption and from trade.

Response: Thanks for the insightful comments. In the Sect. 3.1 of the revised manuscript, we presented the footprint of emissions from production perspective by dividing production-based emissions of each province to three parts: emissions from local consumptions, from consumptions in other provinces through interprovincial trade, and from international consumptions. On average, we found that emissions from local consumptions contributed 62%, 46%, 46%, and 56% of national total emissions for primary $PM_{2.5}$, SO_2, NO_x, and NMVOC respectively, with large variations among different provinces.

Quantification of emissions from both production and consumption perspective will help to identify national or regional responsibility for emission mitigation, and help the developing regions with lower consumption-based emissions gain more supports from developed regions. The importance of consumption-based emission accounting has been emphasized in many studies on global and regional CO_2 emissions (e.g., Peters, 2008; Davis and Caldeira, 2010; Feng et al., 2013). For the first time, our manuscript estimated air pollutant emissions in China from production and consumption perspective at provincial level, by quantifying emissions embodied in interprovincial and international trade of products. This will help policy makers better understanding their responsibilities to air pollution by identifying emissions induced by their consumption activities.

In the meanwhile, tracking emission flows embodied in trade can help to attribute local air pollution to different consumption types, e.g., local vs. regional. With the consumption-based emission inventory developed in this work, we will able to further separate the relative contribution of air pollution by local consumption and regional consumption, by using source-oriented air quality models. Clarifying these relationships will help local government to find an effective way to optimize air quality management decisions toward environmentally sustainable economic growth. Thus, it is of great important to look at emissions from both production and consumption perspective.

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Peters, G. P.: From production-based to consumption-based national emission inventories, Ecol. Econ., 65, 13-23, 2008.

Responses to Anonymous Referee #2:

The manuscript presents a well-designed analysis of questions related to Chinese pollution intensity, as it captures the reader's attention from the introduction. The description of the environmental situation in China, linked to its social and economic consequences, is a perfect starting point when we talk about the Asian giant. The paper provides the scientific community with more evidences, for a better and deeper analysis about the reasons behind the rise of China as the biggest pollutant in recent years. It is easy to identify similar papers that try to contribute to this open debate. In this sense, and as a researcher in the study of international responsibility criteria (producer, consumer or shared), I regard the proposal by the authors as very interesting. The questions tackled in the paper can be likened to some of the consequences of developed countries signing of the Kyoto Protocol for emerging economies like, for example, China. This paper presents the global Chinese environmental situation, understood as the increase in global emissions due to the presence of highly pollutant production processes in emerging regions (rather than countries) inside China. Rich regions (such as the coastal areas) could represent those developed countries that have implemented more and more restricted environmental and energy policies in recent years. Those regions/countries, by means of offshoring processes to other regions/countries with weaker environmental policies, have avoided territorial or producer responsibility for emissions (as accounted under the Kyoto Protocol), but have caused, supposedly, an increase of Chinese/global emissions. From my point of view, the identification of the question, the relation to social and economic costs, and the characterization of some policy implications, are the most interesting contributions of the paper. The model proposed is not new, as the consumption-based approach in a MRIO framework is a well-recognized model. However, the selection of the air pollutants and the detailed analysis of the Chinese interregional trade relationships, also provides the scientific community with useful tools and evidences. In this sense, I would say that the paper could had been a little bit more ambitious, once the scope is presented and the implications and objectives are defined. Some of these ideas are commented in the next section.

Responses: We appreciate for the encouraging comments from the reviewer, which enhanced our confidence in the contribution of this work to the scientific community. We further emphasized the objective and implication of this work in the abstract, introduction, and conclusions of the revised manuscript. We clearly stated that this work is the first study which quantified consumption-based air pollutant emissions for each province in China and tracked virtual emission flows of air pollutants embodied in China's interprovincial trade. As pointed out by the reviewer, the results from this work could help to better understand the responsibility for air pollutant emissions in China, and further evaluate the potential health impact of trade activities by using chemical transport models. We also thank the reviewer for the specific suggestions, which are addressed below.

Related to the allocation criterion chosen in this paper (the consumption-based perspective)*: It would have been interesting to prove or, at the very least, to cite the implications of the implementation of other criteria based on sharing emissions between agents. The application of a shared responsibility criterion like the one proposed by Lenzen*

and Gallego (2005), Cadarso et al. (2012) or Hoekstra and Wiedmann (2014) could help northern and central Chinese regions to assume the increase of costs derived from mitigation policies. Sharing emissions between agents participating in the pollutant activity could contribute to a better solution of the problem as producers and consumers are both involved in emissions reduction.

Responses: Many thanks for the insightful suggestion. In response to this comment, we added following discussion in the conclusion section of the revised manuscript. "*It should be noted that although the results derived from this work could help the policy makers to better understand the responsibility of pollution from consumption perspective, splitting the share of responsibility between producers and consumers is more complicated as producers also gain economic benefit when emitting pollutants (Barrett et al., 2013). Application of shared responsibility criterion (e.g., Gallego and Lenzen, 2005; Cadarso et al., 2012; Hoekstra and Wiedmann, 2014) which involves both producers and consumers in emission reduction could help developing provinces in China to assume the increase of costs derived from mitigation policies and contribute to a better solution of the problem*."

Eco-Labels: *The introduction of an Eco-Labelling system could be another alternative, looking for incentives to improve the efficiency of both existing and new technologies not only from the perspective of technology transfer, but also involving consumers and their decisions. In this case, the consideration of global production chains implies some limitations. O'Rourke (2014) highlights some of them: limitations on sustainability measurements of the supply chains, limitations of data supplied to decisions-makers (consistent and proved models) or disincentives for firms to pay the full costs of supply chains (key limitation). The third point is the most relevant as firms are the agents that decide to outsource their production chains. The implication of firms assuming their share of responsibility is needed, following the line presented in Skelton (2014), already quoted by the authors, or in the control criterion proposed by López et al. (2014).*

Response: We agree. We have revised the manuscript (in Sect. 4.2) according to the suggestion, as follows: "*Economic stimulus or penalty instigated by leading companies can help reduce the emissions of its suppliers more effectively as companies are the agents that decide to outsource their production chains (O'Rourke, 2014), thus can exerting a cleaning effect on its upstream supply chains more easily (Skelton, 2013). Eco-Labelling system could achieve efficiency gains by producers which can be monitored by regulative bodies. Consumer choices in eco-labelling can be a great incentive for companies to adopt such scheme in order to promote market competitiveness (Grundey and Zaharia, 2008).*"

Emissions Trading Scheme: *Another potential improvement for the paper could have been to take into account or at least cite the Chinese Emissions Trading Scheme (ETS), similar to the European Union Trading System, that is currently under evaluation in China (Guan et al. 2014). Like Barrett et al. (2014) suggest, and given the consumer orientation of the paper, the future evaluation of this ETS under the consumer perspective could be interesting.*

Response: Thanks for the suggestion. We have added the following sentence in the revised manuscript: "*The pilot phase of China's Emissions Trading Scheme (ETS) on CO_2, SO_2, and NO_x has proven its effectiveness in emission reductions, expanding the ETS system across*

China can be used to mitigate air pollutant emissions".

Technology transfer: *From my point of view, the technology transfer is not the only option that can contribute to solve the problem. The establishment by policy makers of some limitations to specific new installations which exceed a fixed benchmarking could also be part of the solution. There are some examples for the European Union. The case of the restriction to the use of coal in electricity generation in Spain and some European Union countries is an example (Zafrilla 2014).*

Response: Thanks for the suggestion. In the revised manuscript, we revised the statement as below: "*Technology transfer between developed and developing regions should play a leading role in joint actions for regional or interregional air pollution control. For developed regions, industrial transfer should be accompanied by technology transfer; for less developing regions, higher emission standard should be established for new installations that exceed a fixed benchmarking, thus reducing the increment of emissions.*"

Taxes: *Another interesting solution or alternative could be the transfer of environmental impacts to consumers via environmental taxation. Consumers can guide the economy to a sustainable path changing their consumption patterns. In the case of one country (China), it is possible to highlight some advantages of the establishment of those taxes for international trade. Trade wars are not possible between regions after the implementation of the tax. And there is no risk of carbon leakage as only one government designs, collects and redistributes the environmental tax.*

Response: Thanks for the insightful suggestion. We have added the discussion on environmental tax in Sect. 4.2 of the revised manuscript. *Although China has achieved great progress in technology improvements and pollution intensity reduction, total emissions are still on the rise as improvements in technology efficiency were offset by increasing consumptions (Liang et al., 2014; Guan et al., 2014). Taxes can be used to transfer environmental impacts to consumers, thus reduce the consumption volume and related emissions.*

Pollution haven hypothesis: *After reading the paper, the reader could conclude that the pollution haven hypothesis (PHH) exists among Chinese regions due to the differences between their pollution intensities. Nevertheless, and following Zhang et al. (2014), this evidence is not proved for CO2 emissions; in fact, they find the opposite. The estimation of the Balance of Avoided Emissions (BAE) shows an almost negligible positive figure (PHH) for the electricity sector. For the whole economy, the sign of the BAE is negative, as a consequence of the industrial relocation to inland provinces. This result shows that there are not relevant differences in pollution structures between Chinese regions. The relocation of parts of the production chains does not imply an increase in emissions. Understanding this, the most interesting conclusion of this paper should be the evaluation of how location, concentration and subsequent atmospheric transportation of pollutant particulates affect health. A potential extension using an Atmospheric Chemical Transport model would improve the usefulness of the paper.*

Response: Unlike CO_2, emission intensity of air pollutants in developing regions are much

higher than that in developed regions due to lack of emission control measures (e.g., desulfurization devices). Outsourcing air pollutant emissions within China could result in an increase of total emissions. Emission transfer of air pollutants due to the redistribution in emissions could have potential significant effects on regional air quality. However, as pointed out by referee #3, the impact of emission transfer on human health could be negative or positive, because emissions may transfer to regions with better dispersion conditions or less population. We have clarified this point in the revised manuscript. Investigating the air pollution and health impact caused by cross-regional industry transfer is a very interesting and important topic, but we believe that it is beyond the scope of current paper. The consumption-based emission inventory developed in this work has provided a good basis for consumption-based health benefit evaluation, and we will extend this work in the future.

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Guan, D., Hubacek, K., Tillotson, M., Zhao, H., Liu, W., Liu, Z., and Liang, S.: Lifting China's Water Spell, Environ. Sci. Tec., 48, 11048-11056, doi:10.1021/es501379n, 2014.

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Responses to Anonymous Referee #3:

The authors estimate the air pollutants embodied in inter provincial and international trade for China using an input-output approach. The fraction of emissions embodied in inter provincial trade are similar in magnitude to the fraction in international trade. While the interprovincial results appear to be a new contribution, the manuscript should be rewritten to distinguish this study from previous work.

Response: Thanks for the suggestions. We have rewritten the abstract and introduction part of the manuscript, to clearly state that this work is the first study which quantified consumption-based air pollutant emissions for each province in China and tracked virtual emission flows of air pollutants embodied in Chinese interprovincial trade. Using the approaches developed in this work, we separated the relative contribution of local consumption and regional consumption to air pollutant emissions in each province, constructed a consumption-based emission inventory for each province, and tracked the emission flows embodied in interprovincial trade. To our best knowledge, all these results are presented for the first time for air pollutant emissions in China. We also added a conclusion section in the revised manuscript, to emphasize our unique contribution presented in this work.

Major Comments

The introduction in the manuscript does not identify the unique contribution of this study. In particular the Lin et al. (2014) study appears to have done something very similar. The present manuscript needs to identify the differences in approach from previous work and provide evidence as to why these differences are important and worth investigating. It seems that this might be that the study adds a province-level analysis... but this needs to be stated and its importance needs to be justified.

Response: Thanks for pointing out this. Lin et al. (2014) investigated air pollutant emissions embodied in China's international trade and their impact to the global environment with a focus on air quality in the United States. The objective of this work is to understand air pollutant emissions embodied in China's interprovincial trade, which is quite different from Lin et al. (2014). Lin et al. (2014) used a Single-Region Input-Output (SRIO) model, which is able to quantify emissions embodied in trade, but not able to track the trade-embodied emission flows from different regions. In this work, we used a Multi-region Input-Output (MRIO) model framework, to track the emission flows embodied in interprovincial trade. This is of great importance because developed regions always consumed more products but transferred emissions to developing regions through trade. As China is an uneven developed country, rich regions could avoid producer emissions by offshoring productions to poor regions, resulting redistribution of emissions and pollution in the country. The results from this work will help the community to reveal the social-economic drivers behind the air pollutant emission growth in China and aid the policy makers to better understand their responsibilities to air pollution by identifying emissions induced by their consumption activities. In the revised manuscript, we have rewritten the abstract and introduction part and added a conclusion section, to identify the importance and unique contribution of this study. We also revised the Sect. 3.4 to avoid redundant discussions on international trade, which is

thought to be a minor contribution of this work.

The results that 15-23% of emissions are embodied in foreign trade is very similar to the 17-36% reported in Lin et al. (2014) so perhaps this is not a new results and should not be highlighted in the abstract.
Response: Agree. This sentence has been removed from the abstract.

"However, if the response is to shift industry out of these cities without changing consumption patterns, the result of the regulations may be an increase in the total amount of pollution emissions and little or no improvement in air quality, since there will be an increase in emissions through transportation along the geographically extended supply chains and also because that the general low efficient production in less regulated areas." This sounds like a critical motivation for this study but the opposite may be true. If consumption stays the same but emissions are shifted out of megacities then that would have two effects to reduce the impact of air quality. First, the emissions might be more dispersed in space which would dilute the concentrations. Second, the emissions would be further from the high population densities which would result in dilution from atmospheric mixing and reduce exposure impacts. It's not clear to me if the increase in transportation of goods and the less efficient production in less regulated areas would be more important or less important than the factors that I mention above. To investigate this trade-off you would need to include a health assessment model (e.g. BENMAP).
Response: Thanks for the comment. We agree that the impact of emission transfer on human health could be positive or negative, as pointed out by the reviewer. In the revised manuscript, we have changed the statement as follows. *"However, if the response is to shift industry out of these cities without changing consumption patterns, the result of the regulations may be an increase in the total amount of pollution emissions, since there will be an increase in emissions through transportation along the geographically extended supply chains and also because that the general low efficient production in less regulated areas. The redistribution in emissions could have potential significant effects on regional air quality."* We further discussed this issue in the conclusion section of the revised manuscript. Investigating the air pollution and health impact caused by cross-regional industry transfer is a very interesting and important topic, but we believe that it is beyond the scope of current paper, and the results and policy implications presented in this work is worthy for publication in ACP. The consumption-based emission inventory developed in this work provides a good basis for consumption-based health benefit evaluation, and we will extend this work in the future.

Minor Comments
"These particles are known..." Previous sentence is talking about gases and particles so might need to rewrite in this sentence "The primary PM2.5 particles..."
Response: Corrected.

The results that 15-23% of emissions are embodied in foreign trade is a bit lower than the 17-36% reported in Lin et al. (2014). The discussion section should include some reasons for this difference

Response: The differences between Lin et al. (2014) and this work are mainly due to differences in methodologies. As mentioned above, Lin et al. (2014) used a Single-Region Input-Output (SRIO) model, while we used a Multi-Region Input-Output (MRIO) model framework. SRIO used national average emission intensity when calculating export embodied emissions, which will overestimate emissions in coastal provinces where emission intensities are lower than national average. In MRIO framework, embodied emissions were calculated for each province using its own emission intensity. Estimates in Lin et al. (2014) would be then higher than ours, as export embodied emissions are dominant by coastal provinces. We explained the reasons of differences in Sect. 3.4 of the revised manuscript.

"Allow for the embodied emission from other regions, the pollution embodied in these regions' products exports accounts more (68–75 %)." Please rewrite.

Response: Thanks for pointing out this. It is an improper statement and has been removed in the revised manuscript.

Reference:

Lin, J., Pan, D., Davis, S. J., Zhang, Q., He, K., Wang, C., Streets, D. G., Wuebbles, D. J., and Guan, D.: China's international trade and air pollution in the United States, P. Natl. Acad. Sci. USA, 44,7771-7776, doi:10.1021/es101094t, 2014.