# Response 2

We thank the reviewer for the valuable and constructive comments and suggestions, which have helped to improve the quality of the manuscript. We have studied comments carefully and made corrections accordingly. Below are our responses to the comments from reviewer. The response follows each comment in black color and questions in blue color.

Reviewer 2:
Review comments:
This study applied regional CTMs to study the future climate changes on the inter-regional transport of PM2.5 in China. The topic is very interesting. However, the methods described by the authors worried me. In the methods section, the authors listed the equation 2 for the future climate dynamical downscaling. I am not very convinced by the feasibility as described. Are those 5 CMIP6 model outputs were downscaled together and averaged out, or did the authors calculate the climate changes simulated by the 5 CMIP6 models and then add them into the FNL2015 data? If the latter, how is that possible?
Response: We thank the reviewer for this valuable comment. We have added 5 CMIP6 models , The results of the additional simulation have been added to the revised manuscript

$$WRF_{\mathrm{in}put\,2050} = FNL_{2015} + \Delta CMIP6_{\mathrm{ssp}} \tag{1}$$

According to Liu et al., (2021a) described that ΔCMIP6ssp is the 5-year CMIP6 multimodel ensemble mean change signal under the SSP585 or SSP126 emission scenario.

$$\Delta CMIP6_{\mathrm{ssp}} = CMIP6_{2048\text{-}2052} - CMIP6_{2013\text{-}2017} \tag{2}$$

The perturbation term △CMIP6ssp takes into account changes in wind direction, temperature, humidity, sea surface temperature, sea level pressure and sea ice. This quasi-climate simulation approach minimizes the number of scenarios that need to be simulated, considering that a perturbation added to the base of each base year does not require a multi-year averaging repetition of the baseline.
Above method is the pseudo-global warming (PGW) simulation, which is a new method of dynamical downscaling proposed by Kitoh et al (2016). The PGW simulation is similar to the traditional dynamical downscaling method, but the boundary conditions are a combination of reanalysis information and the differences between the future scenario and the baseline simulated by the global climate model.
The PGW simulation method only requires the monthly average output of climate models, which greatly reduces the heavy workload of traditional downscaling and makes it easier to study multiple climate models and climate change scenarios; Meanwhile, the PGW simulation method also has the advantages of reducing the systematic errors of climate models and avoiding the uncertainties caused by inter-annual oscillations in a short integration time. Therefore, PGW simulation

methods has been shown to have great potential for accurate downscaling of future climate and has been widely used in meteorological research (Kawase et al., 2013, Kawase et al., 2009, Lauer et al., 2013, Nayak et al., 2019,Takemi et al., 2016, Taniguchi et al., 2015, Taniguchi et al., 2020).

However, to address the reviewer's concern, we also conducted the simulation with the five climates downscaling individually, and analyze all together to make a clear variation of results rather than one single value. We have modified all the results corresponding in the revised manuscript.

Reference

Liu S, Xing J, Wang S, et al. Health benefits of emission reduction under 1.5° C pathways far outweigh climate-related variations in China[J]. Environmental Science & Technology, 2021a, 55(16): 10957-10966.

Kitoh A, Ose T, Takayabu I. Dynamical downscaling for climate projection with high-resolution MRI AGCM-RCM[J]. Journal of the Meteorological Society of Japan. Ser. II, 2016, 94: 1-16.

Kawase, H.; Hara, M.; Yoshikane, T.; Ishizaki, N. N.; Uno, F.; Hatsushika, H.;Kimura, F. Altitude dependency of future snow cover changes over Central Japan evaluated by a regional climate model. J. Geophys. Res.: Atmos.2013,118,12444–12457,DOI: 10.1002/2013JD020429

Kawase, H.;Yoshikane, T.;Hara, M.;Kimura, F.;Yasunari, T.;Ailikun, B.;Ueda, H.;Inoue, T.Intermodel variability of future changes in the Baiu rainband estimated by the pseudo global warming downscaling method.J. Geophys. Res.: Atmos.2009,114,D24110 DOI: 10.1029/2009JD011803

Lauer, A.; Zhang, C. X.; Elison-Timm, O.; Wang, Y. Q.; Hamilton, K. Downscaling of Climate Change in the Hawaii Region Using CMIP5 Results: On the Choice of the Forcing Fields.J. Clim.2013,26,10006–10030,DOI: 10.1175/JCLI-D-13-00126.1

Nayak, S.; Takemi, T. Dynamical Downscaling of Typhoon Lionrock (2016) for Assessing the Resulting Hazards under Global Warming. J. Meteorol. Soc. Jpn.2019,97,69–88, DOI: 10.2151/jmsj.2019-003

Takemi, T.;Ito, R.;Arakawa, O.Effects of global warming on the impacts of Typhoon Mireille (1991) in the Kyushu and Tohoku regions. Hydrol. Res. Lett.2016,10,81–87,DOI: 10.3178/hrl.10.81

Taniguchi, K.; Sho, K. Application of the Pseudo Global Warming Dynamic Downscaling Method to the Tokai Heavy Rain in 2000. J. Meteorol. Soc. Jpn.2015,93,551–570, DOI: 10.2151/jmsj.2015-043

Taniguchi, K.; Tajima, Y.Variations in extreme wave events near a South Pacific Island under global warming: case study of Tropical Cyclone Tomas. Prog. Earth Planet. Sci. 2020, 7, 1– 16, DOI: 10.1186/s40645-020-0321-y

To clarify this point, We have clarified this point in the revised manuscript as follows.

(Page 5, line131-138) "This quasi-climate simulation approach minimizes the number of scenarios that need to be simulated, considering that a perturbation amount added to the base of each baseline does not need to be repeated by averaging the base year over many years (Kawase et al., 2013).The biggest difference is that the boundary conditions are combined and come from the reanalysis information and the difference between the future year and the base year simulated by the global climate model. The advantage of this method is that it minimizes the workload of dynamical downscaling and also reduces the systematic errors of climate models, so the new method of quasi-climate simulation has been widely used (Lauer et al., 2013; Minamiguchi et al., 2019; Nayak and Takemi, 2019; Taniguchi and Tajima, 2020)."

When simulating the future climate changes, the authors only ran 4 months (Jan, April, July, October) for the two scenarios, with a few days as spin-up. This is not acceptable to consider the influence of climate variability on the simulation of air pollutants changes.

Response: We thank and accept the reviewer for this valuable suggestion. As the reviewer suggested, we have run all complete 12 months for both 2015 baseline and 2050 two scenarios, including REF and CBE emission levels (according to reviewer1's suggestion), to reduce the uncertainty of climate variability and better understanding out the future impacts between emissions and meteorology.

On the one hand, by comparing the simulation of two emission scenarios (REF and CBE), our results suggest that the changes in regional transport from emission controls are much greater than that due to future meteorological fluctuations.

On the other hand, by comparing the simulation of multi-climate models (BCC, MRI, IPSL, EC, CNRM), we found the $PM_{2.5}$ regional transport of meteorological fluctuations are still uncertain range (-7.19 $\mu g/m^3$ to 2.59 $\mu g/m^3$).

To clarify this point, we have provided additional explanation in the revised manuscript as follows.

(Page 4, line87) "A 7-day spin-up simulation is conducted to eliminate the influences of initial condition."

(Page 5, line147-153) "Future emissions under controlled pathway is the same as our previous study which estimates the co-benefits of energy policy in reducing air pollution (noted as co-benefit energy scenario, CBE). Specifically, in comparison with the REF scenario, the CBE decreases the $PM_{2.5}$ (73.3%), $SO_2$ (77.6%), NOx (77.3%), and VOC emission (60.0%) in 2050. Here, sensitivity analysis was conducted with different combination of meteorology and emission scenarios (Table 1). The same baseline anthropocentric emissions are used in Case-Base, Case-2050-SSP126-REF and Case-2050-SSP585-REF but with different meteorological conditions, indicating their differences are only driven by the meteorology changes. Similarly, only meteorology varies in Case-2015-CBE, Case-2050-SSP126-CBE and Case-2050-SSP585-CBE which are used to analyze the change in emissions(Liu et al., 2021a; Xing et al., 2020). We simulated 12 months as a year."

Reference

Liu, S., Xing, J., Wang, S., Ding, D., Cui, Y., and Hao, J.: Health Benefits of Emission Reduction under 1.5 degrees C Pathways Far Outweigh Climate-Related Variations in China, Environ. Sci. Technol., 55, 10957-10966, 10.1021/acs.est.1c01583, 2021.

Xing, J., Lu, X., Wang, S., Wang, T., Ding, D., Yu, S., Shindell, D., Ou, Y., Morawska, L., Li, S., Ren, L., Zhang, Y., Loughlin, D., Zheng, H., Zhao, B., Liu, S., Smith, K. R., and Hao, J.: The quest for improved air quality may push China to continue its CO2 reduction beyond the Paris Commitment,

P. Natl. Acad. Sci. Usa., 117, 29535-29542, 10.1073/pnas.2013297117, 2020.

(Page13-14, line308-319) “However, the effects of meteorological fluctuations are still uncertain range (-7.19 μg/m$^3$ to 2.59 μg/m$^3$). Fig S5 and S6 shows the differences in details between the different models. We found that CNRM and EC models display a wide range of overall fluctuations among all regions. Excluding these two models, the overall variation impacts of meteorological fluctuations would be less than 1μg/m$^3$. Furthermore, a significant dipole distribution exists in the IPSL model, which shows a decreased concentration in NCP and FW regions and an increased concentration in YRD and HH regions. The other three models (BCC, MRI and ensemble mean models) present consistent results. Regional transport of different models also reflects the change of source and receptor under future projected scenarios (Fig. S7). Furthermore, similar patterns are presented in CBE scenarios (Fig. S8), with the concentration of regional transport less than 0.5μg/m$^3$ and a change of contribution of less than 2%, indicating that future meteorological fluctuations driven by the climate change has limited effects on the regional transport of $PM_{2.5}$. Apparently, emission reductions lead to a substantial reduction in $PM_{2.5}$ regional transport, which far outweigh the influences of meteorological fluctuations driven by future climate change.”

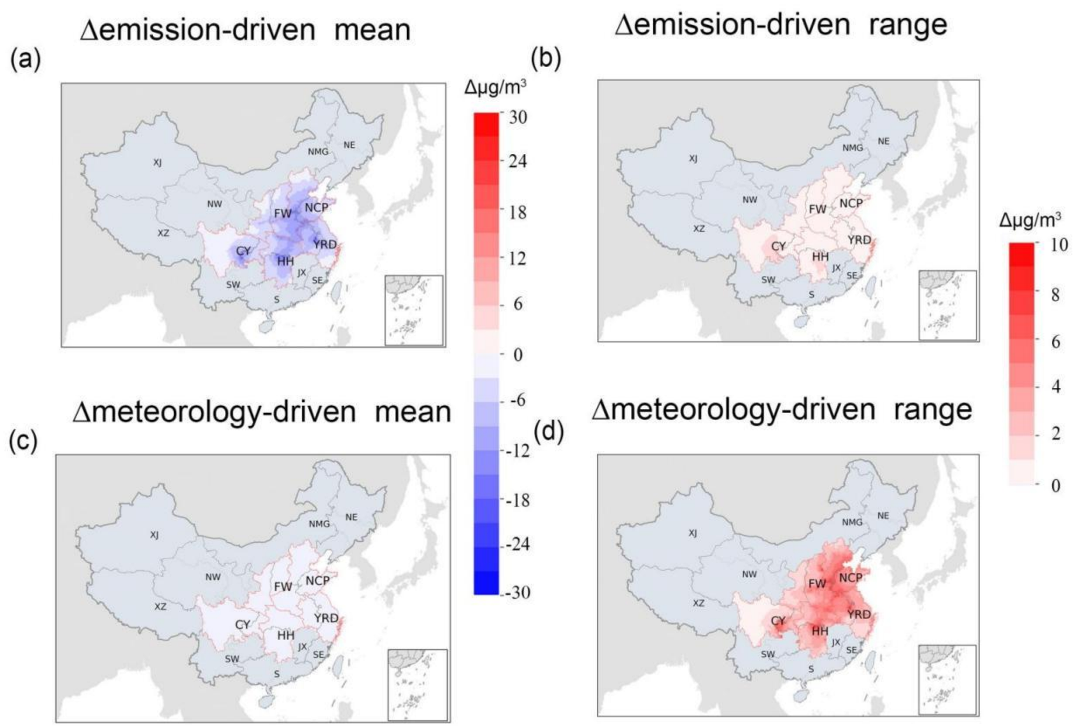


**Figure 5** The average and variation range of Δemission-driven (a,b) and Δmeteorology-driven (c,d) impacts on the change of $PM_{2.5}$ regional transport.

In addition to the changed distribution of $PM_{2.5}$ regional transport across China in future 2050 scenarios, climate change also plays variable influence on each provinces/regions.

We have clarified this point in the revised manuscript as follows.
(Page14-15, line 324-333) "Fig 6 summarizes regional transports and interactions of $PM_{2.5}$ in five key regions in 2050. Similarly, the Δemission-driven impacts are much larger than the Δmeteorology-driven impacts on regional transport in all five regions. The local contributions (noted as ΔLocal in Fig 6) are substantially reduced (-4.5% to -10.4%) due to the emission reduction, which far outweighs the influence from meteorological fluctuations (-2.9% to 2.5%). Correspondingly, across-regional transport contributions (noted as ΔART in Fig 6) are increased (3.3% to 11.8%) by the emission reduction in all five regions. However, the inner-regional transport contributions (noted as ΔIRT in Fig 6) are barely changed (-2.5% to 2.3%) due to either emission reduction or meteorological fluctuations. Apparently, along with the future emission controls, the reduction in local contributions will also lead to an enhancement in the contribution from across-regional transport rather than the inner-regional transport. Therefore, across-regional transport (ART) contributions rise significantly under future strict control of pollutant emissions, such results highlighted the significance of joint-provincial cooperation."

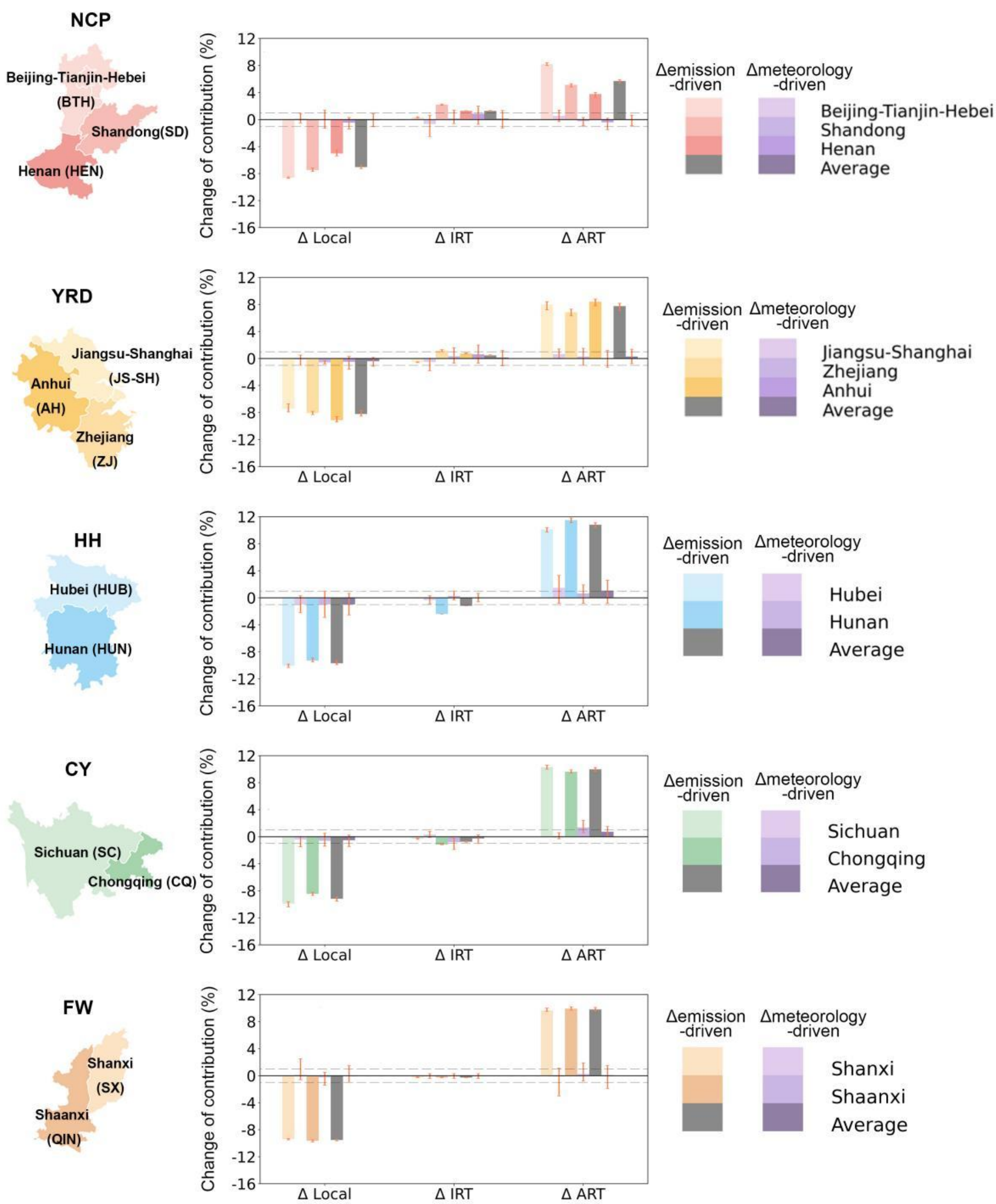


**Figure 6.** Comparison of Δemission-driven and Δmeteorology-driven impacts on local contributions (ΔLocal), Inner-regional Transport (ΔIRT) and Across-regional Transport (ΔART) in five key regions.

(Page16-17, line343-355) "The future change of the interactions among key regions is shown in Fig.7. Similarly, emission controls significantly reduce the across regional interactions, which largely outweighs the influence from the meteorological fluctuations. Among all five regions, the NCP presents the greatest change due to the Δemission-driven (Fig. 7a and 7b). More specifically, the absolute decreases the most by 12.09 μg/m$^3$, followed by NCP to HH receptor (8.13 μg/m$^3$). However, the relative impacts is increased in most of regions, as the impacts of NCP to YRD increased by 2.69 %, and the NCP to HH receptor increased by 2.67 %. There were fewer changes due to Δmeteorology-driven, with a slight increase of 0.78 μg/m$^3$ (0.29 %) from NCP to YRD receptor and 0.64 μg/m$^3$ (0.73 %) from NCP to HH receptor, which is much smaller compared to the influence of Δemission-driven. The CY region shows the weakest connection with other areas, with the least variation (less than 1 %) in 2050 scenarios. Less $PM_{2.5}$ across-regional transport to CY and FW regions in future emission and climate change, implying the decreased $PM_{2.5}$ concentrations from other sources to CY and FW regions."

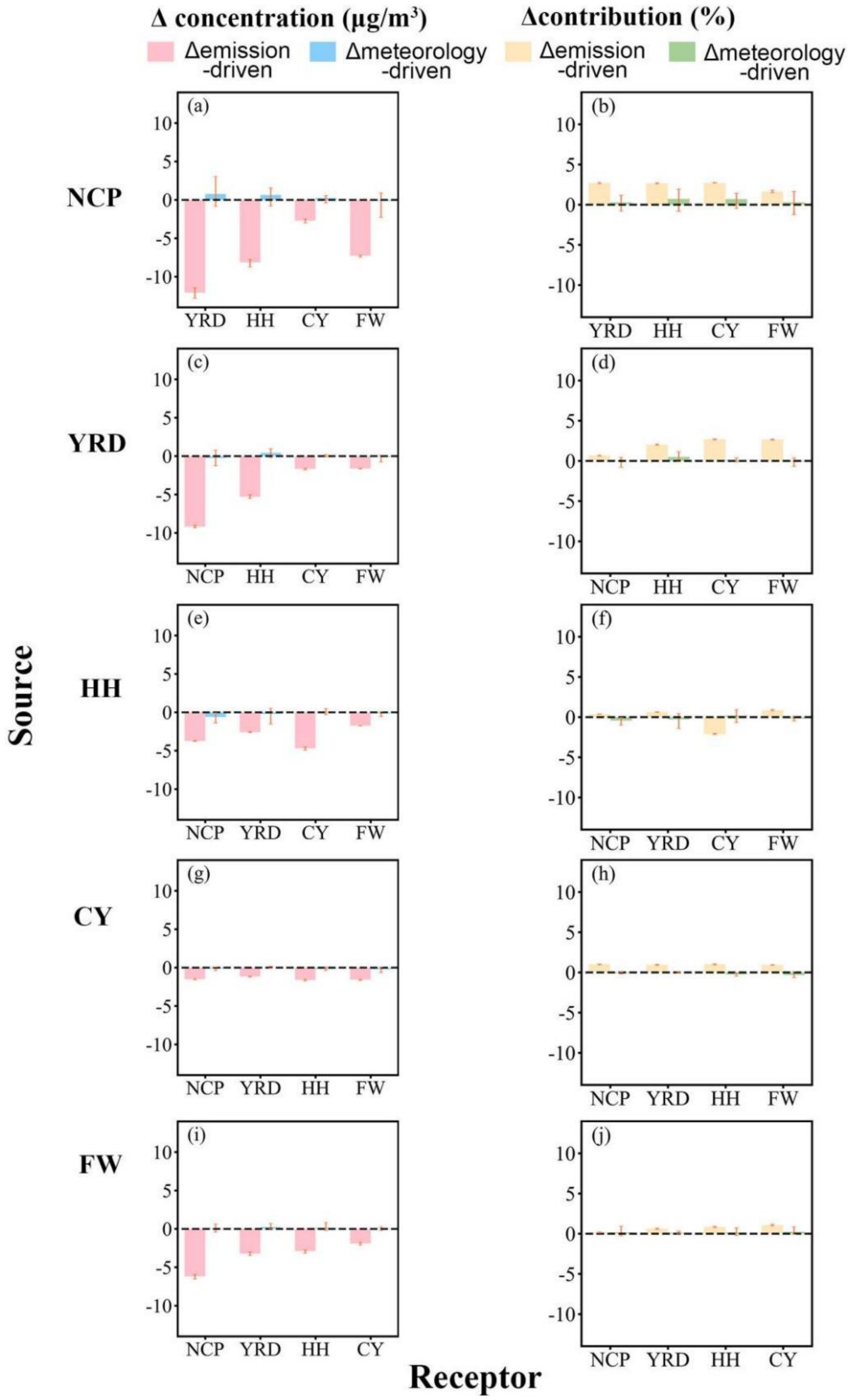

**Figure 7.** Similar to Figure 3, the relationship between five sources and receptors in 2050 (red and yellow bar show Δemission-driven, blue and green bar show Δmeteorology-driven). Each subplot represents the effect of a single source on the other four receptors.

Editorial comments:

L22: “meteorology” to “climate”

Response: Thanks for the good suggestion.

We changed the word in the manuscript.

L26: change to “suffer”

Response: Thanks for the good suggestion.

We revised the word “suffer” to “polluted by”

No Graphical abstract needed for the journal. The short summary is not needed in the manuscript either, but only during submission.

Response: Thanks for the good suggestion.

We have removed both graphical abstract and short summary in the manuscript.

L42: distinguish the three “Wang et al., 2014”. Also the paper needs to update the recent studies about the PM2.5 pollution in China.

Response: We thank the reviewer for the comment. We have removed three “Wang et al., 2014” and replaced with recent references in the manuscript.

Reference

Wang P, Chen K, Zhu S, et al. Severe air pollution events not avoided by reduced anthropogenic activities during COVID-19 outbreak[J]. Resources, Conservation and Recycling, 2020, 158: 104814.

An Z, Huang R J, Zhang R, et al. Severe haze in northern China: A synergy of anthropogenic emissions and atmospheric processes[J]. Proceedings of the National Academy of Sciences, 2019, 116(18): 8657-8666.

Song C, Wu L, Xie Y, et al. Air pollution in China: status and spatiotemporal variations[J]. Environmental pollution, 2017, 227: 334-347.

Wang X, Dickinson R E, Su L, et al. PM2. 5 pollution in China and how it has been exacerbated by terrain and meteorological conditions[J]. Bulletin of the American Meteorological Society, 2018, 99(1): 105-119.

Li G, Fang C, Wang S, et al. The effect of economic growth, urbanization, and industrialization on fine particulate matter (PM2. 5) concentrations in China[J]. Environmental science & technology, 2016, 50(21): 11452-11459.

L46: add "annual mean"

Response: Thanks for the good suggestion.

We have added "annual mean" words as follows:

(WHO) Air Quality Guidelines (5 μg $m^{-3}$ annual mean).

L51: I assume the 411,000 premature deaths was in China?

Response: According to Zhang (2017), 411,000 premature deaths was in 2007 worldwide.

The original description is as follows:

We find that, of the 3.45 million premature deaths related to $PM_{2.5}$ pollution in 2007 worldwide, about 12 per cent (411,100 deaths) were related to air pollutants emitted in a region of the world other than that in which the death occurred, and about 22 per cent (762,400 deaths) were associated with goods and services produced in one region for consumption in another.

Reference

Zhang, Q., Jiang, X., Tong, D., Davis, S. J., Zhao, H., Geng, G., Feng, T., Zheng, B., Lu, Z., Streets, D. G., Ni, R., Brauer, M., van Donkelaar, A., Martin, R. V., Huo, H., Liu, Z., Pan, D., Kan, H., Yan, Y., Lin, J., He, K., and Guan, D.: Transboundary health impacts of transported global air pollution and international trade, Nature, 543, 705, 10.1038/nature21712, 2017.

L70: I am pretty positive that "Dedoussi et al., 2020" study has nothing with China's carbon policy.

Response: Yes, "Dedoussi et al., 2020" occurs in the United States, which has nothing with China's carbon policy. We have removed this reference in the manuscript (line 71).

L82: distinguish the two Liu et al., 2021 studies. The same as in L116-117.

Response: Thanks for the good suggestion. We have distinguished the two Liu et al., 2021 studies as 2021a and 2021b.

Reference

Liu S, Xing J, Wang S, et al. Health benefits of emission reduction under 1.5° C pathways far outweigh climate-related variations in China[J]. Environmental Science & Technology, 2021a, 55(16): 10957-10966.

Liu S, Xing J, Westervelt D M, et al. Role of emission controls in reducing the 2050 climate change penalty for PM2. 5 in China[J]. Science of the Total Environment, 2021b, 765: 144338.

L88: please find the right reference for the CMAQ AER6 module.

Response: Thanks for the good suggestion.
We have checked and updated the reference in the manuscript (line 93).

Reference
Appel K, Pouliot G, Simon H, et al. Evaluation of dust and trace metal estimates from the Community Multiscale Air Quality (CMAQ) model version 5.0[J]. Geoscientific Model Development, 2013, 6(4): 883-899.

L96: define “regional transport” and “regional level” here. This is very confusing to understand the authors’ motivations.
Response: We thank the reviewer for pointing out those two fuzzy concepts.
“regional transport ” means across-regional transport (ART) regional transport.
“regional level” indicates five source and receptors in Figure S1b.
In order to clarify this concept, we changed the original paragraph to line 156 of the section 2.3. We have re-write the sentence and clarified this point in the revised manuscript as follows:

(Page 6, line 158-159)“We also quantify the impacts of across-regional transport (ART) regional transport at regional level (see Supplemental Material Fig. S1b, five targets sources and receptors, including several provinces)”.

L108-109: The authors regrouped the 21 “quasi-provinces” into five regions, but then the authors claimed that they were studying the city clusters. This is very misleading for the readers.
Response: We thank the reviewer for pointing out those fuzzy concepts. We re-write the sentence as follows:

(Page 4, line 113-115) “To analyze large-scale regional transport across and within severely polluted regions, we further combine 21 quasi-provinces into five key target regions, which defined as across-regional transport (ART) (see Fig. S1b five colors):”

”.

L129: reorganize the sentence. “their” is not very clear for which was referred here.
Response: Thanks for the good suggestion.
We re-write the sentence as follows:

(Page5, line 150-152) “The same baseline anthropocentric emissions are used in Case-Base, Case-2050-SSP126-REF and Case-2050-SSP585-REF but with different meteorological conditions, indicating their differences are only driven by the meteorology changes.”

L149: "defined as the sum of contribution except for local emission produced" describe how this was calculated.

Response: Thanks for the good suggestion.

We have added the calculated formula (3) and (4), and re-write the sentence as follows:

(Page 7, line 187) "(the result of equation (3) and (4))".

L150: where are those "densely populated areas"?

Response: Thanks for the good suggestion.

We used those "densely populated areas" intended to demonstrate that those provinces present poor air quality is closely related to dense population. But we didn't show the population distribution figure, so we have removed some inaccurate words in the manuscript.

L155-156: the explanation for this does not make any sense.

Response: Thanks for the good suggestion.

We have removed this explanation in the manuscript.

L166: "In general, the largest source of PM2.5 is local contribution," I found this statement is not quite true. If you count the dark colors in Fig 1d, there are 11 out of 21 regions that local emissions dominates more than 50% of total PM2.5. It seems to me that the local sources are as important as regional transport.

Response: We thank the reviewer for this valuable comment. The contribution of regional transport changed due to we updated calculated method (see Page6). Besides, we simulate all 12 months and use new initial conditions of the CMAQ-ISAM model. Therefore, the result is different than before.

We revised the sentence as follows:

(Page8, line204-205)"As indicated by Fig 1(d), the contribution of regional transport is prevailing rather than local sources in more than 50% regions of the total 21regions."

L199: these "inner-regional transport (from nearby provinces within the same region), and across-regional transport" should be defined earlier in the methods. So the readers will understand what the authors are trying to study.

Response: We thank and accept the reviewer for this valuable suggestion. We have defined the two concepts in the section 2.2 study area as follows:

(Page 4, line 113-115) "To analyze large-scale regional transport across and within severely polluted regions, we further combine 21 quasi-provinces into five key target regions, which defined as across-regional transport (ART) (see Fig. S1b five colors)."

(Page 5, line 119-120) “Noted that within those five target regions, inner-regional transport (IRT) is defined as nearby provinces of Chinese geographical division. (see Fig. S1b same color).

Table 1:
Change “2050 friendly climate” to “2050 climate friendly”
Response: Thanks for the good suggestion.
We have corrected the expression in the Table 1 (Page 6).

Fig. 1. In Fig 1 (d), these abbreviations of provinces in China are hard for the authors to comprehend the message from this plot. The authors probably can add the full names in (b) or (c).
Response: Thanks for the good suggestion. We have added the full names of provinces of China in Figure 1 (b).

Fig. 6: put all the legends “(a) Source ” and “(b) Source” on the same levels.
Response: Thanks for the good suggestion.
We have removed the word “Source” in Fig.3 and Fig. 7 legends “(a) Source ” and “(b) Source”