Reply to Reviewer #2:

General comments: This paper attempted to quantify the effect COVID-19 on the evident PM2.5 decline after removing the influences of climate anomalies and expected routine emissions reductions. Combined with GEOS-Chem model experiments, they used both high and low emission scenarios to simulated the percentages of PM2.5 changes due to meteorological conditions which tended to increase PM2.5 in February 2020, particular in North China. And they further extrapolated the PM2.5 change due to expected routine emission reductions to isolate the decline in PM2.5 concentration due to COVID-19 quarantines in the East of China quantitatively. This study presents some interesting results and could help us better understand the response of air quality to the COVID-19. However, I think the author needs to **add some more detailed and rigorous exposition** to present their results. **Before it can be publishable, I would like the authors to address my following comments.**

Major comments

Line 65-75 This section requires a more detailed description of the model evaluation. At the end of this section, the author just showed the model could capture the change of meteorological conditions, with high similarly between simulated and observed PM2.5 data. But it is essential that the performance of this model could reproduced the observed true value of PM2.5 concentration. Please evaluate against observation.

Reply:

The evaluations of model performances were considerably improved in the following two ways and were documented in a separated paragraph (i.e., Lines 86-101).

(1) With the configuration we used, **evaluations between the observed and simulated** $PM_{2.5}$ concentrations in Feb 2017 were added as new Figure S1a and associated analysis were in lines 89-96. Obviously, **mean values of simulated** $PM_{2.5}$ were **consistent with the observations** (Figure S1a). The percentage of standard error / mean equals **5.8% (4.6/79.6) in NC, 7.0% (3.9/55.6) in YRD and 5.4% (3.7/70.8) in HB**, indicating the good performance of reproducing the polluted conditions. The absolute biases were larger in the south of China. The **simulated spatial distribution** was also similar to that of observations in Feb 2017 with **spatial correlation coefficient**

= 0.78.

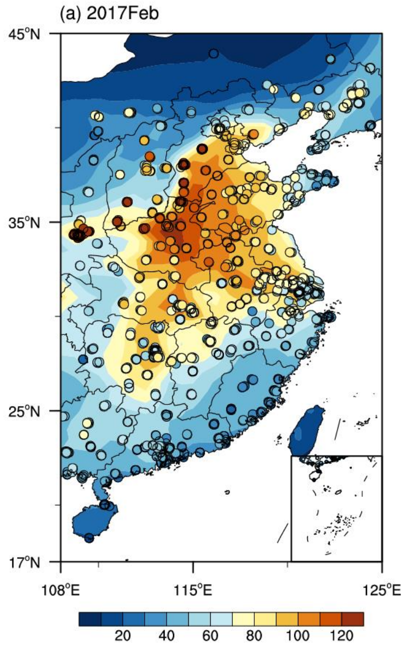

Figure S1a. Spatial distribution of observed (dots) and GEOS-Chem simulated (shading) $PM_{2.5}$ in February 2017.

Furthermore, the ability of GEOS-Chem to reproduce the daily variations of $PM_{2.5}$ in Feb 2020 was also introduced in the old version as below.

changes in February 2020 under a substantial reduction in emissions because of COVID-19 quarantines. In North China (NC), Yangtze River Delta (YRD) and Hubei Province (HB), the correlation coefficients between daily $PM_{2.5}$ observations and simulated data under 2010 (1985) emission scenario reached 0.83 (0.82), 0.67 (0.63), and 0.79 (0.73), respectively. For example, in NC, the simulation could well simulate severe haze events (e.g., from 8–14 and 18–22 February) and good air quality events (e.g., from 15–19 February), reflecting that it has ability to accurately capture the change of meteorological conditions (Fig.

(2) The model configurations were default and **similar with many previous studies**, which were adopted by many previous publications and we also introduced related evaluations in the revised manuscript. Dang and Liao directly evaluated the capacity of models in $PM_{2.5}$ simulations by calculating the normalized mean bias. The simulated spatial patterns of 2013-2017 winter $PM_{2.5}$ were agreed well with the measurements, which was **similar to our evaluations in Figure S1a.** The scatterplot of simulated versus observed **seasonal mean $PM_{2.5}$ concentrations** showed **overestimated** $PM_{2.5}$ concentrations with a normalized mean bias (NMB) of +8.8 % for all grids and an NMB of +4.3 % for BTH (Figure R1a). They also compared the simulated and observed **daily mean $PM_{2.5}$ concentrations** at the Beijing, Shanghai,

and Chengdu grids, which represent the three most polluted regions of BTH, YRD, and the Sichuan Basin, respectively. The model has **a low bias in Beijing** with an NMB of **−9.2 %** and is unable to predict the maximum $PM_{2.5}$ concentration in some cases. For Shanghai and Chengdu, the model **has high biases with NMBs of 18.6 % and 28.7 %**, respectively (Figure R1b). This evaluation also showed a bigger simulated bias in the south of China. The model, however, can capture the spatial distributions and seasonal variations of each aerosol species despite of the biases in simulated concentrations.

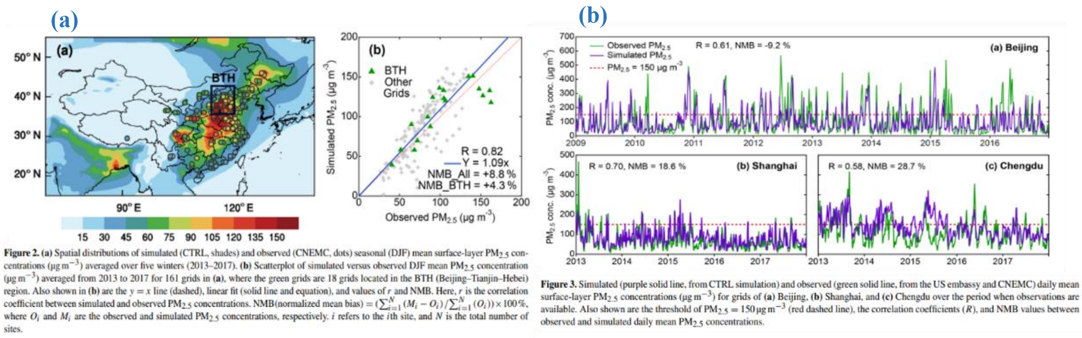

Figure R1. Key Figures in ***Dang and Liao (2019).***

Related references:

Dang, R., and Liao, H.: Severe winter haze days in the Beijing-Tianjin-Hebei region from 1985 to 2017 and the roles of anthropogenic emissions and meteorology, Atmos. Chem. Phys., 19, 10801–10816, 2019.

Revision:

Lines 86-96: GEOS-Chem model has been widely used to examine the historical changes in air quality in China and quantitatively separate the impacts of physical-chemical processes. Here, we simulated the $PM_{2.5}$ concentrations in February 2017 and evaluated the performance of GEOS-Chem (Figure S1a). The values of mean square error / mean equals were 5.8%, 7.0% and 5.4% in North China (NC), Yangtze River Delta (YRD) and Hubei Province (HB), respectively, indicating the good performance of reproducing the haze-polluted conditions. The absolute biases were larger in the south of China, which was consistent with Dang and Liao (2019). They also compared the simulated and observed daily mean $PM_{2.5}$ concentrations at the Beijing, Shanghai, and Chengdu grids, which had a low bias in Beijing and high biases in Shanghai and Chengdu, respectively. The simulated biases possibly affected the subsequent results and brought uncertainties to some extent. The simulated spatial distribution of $PM_{2.5}$ was also similar to that of observations with spatial correlation coefficient = 0.78. We further verified whether the simulations could capture the roles of meteorological changes in February 2020 under a substantial reduction in emissions because of COVID-19 quarantines…….

Line 93 The difference of PM2.5 was linearly decomposed into three parts. I think this is a reasonable approximation, but the author should give more explanation on the rationality of such decomposition.

Reply:

The linear decomposition is definitely a **reasonable and feasible approximation** and must have differences with the reality due to complex atmospheric chemical processes. The reasons for selecting the linear hypothesis were as follows.

(1) **From 2013 to 2019**, the impacts of emission reduction were approximatively linear, which might related to the **enhanced and reinforced control measures in China**. Because the signal of emissions reduction in China had been **particularly strong since 2013**, it could be easily detected and the assumption of a linear reduction in pollution caused by emission reduction was **applicable in China in the past few years**. This linear approximation was employed by many previous studies (Geng et al. 2017; Zheng et al. 2018) and even by **national assessments aimed to evaluate the effects of *Action Plan of Air Pollution Prevention and Control* from 2013 to 2017** (Geng et al. 2020; Wang et al. 2020). We have introduced the evaluated results in lines 137-142.

(2) After disentangling the effects of meteorology, the variations in $PM_{2.5}$ concentrations also **showed linear change** (Figure 5 in our manuscript), which laterally verified the rationality of linear approximation.

(3) Because of the significantly linear reduction of $PM_{2.5}$ due to changing emissions, the linear decomposition or approximation **became reasonable *<u>in China in recent years</u>*** to some extent.

In the revised versions, **we illustrated the linear decompositions were an reasonable estimated approach** and must brought some uncertainties due to ignoring the meteorology-emission interactions, the product of emissions and their loss lifetime (Lines 263-267).

Related references:

Geng, G., Zhang, Q., Tong, D., Li, M., Zheng, Y., Wang, S., and He, K.: Chemical composition of ambient $PM_{2.5}$ over China and relationship to precursor emissions during 2005–2012, Atmos. Chem. Phys., 17, 9187–9203, https://doi.org/10.5194/acp-17-9187-2017, 2017.

Geng, G., Xiao, Q., Zheng, Y., Tong, D., Zhang, Y., Zhang, X., Zhang, Q., He, H., and Liu, Y.: Impact of China's Air Pollution Prevention and Control Action Plan on PM2.5 chemical composition over eastern China, Sci. China Ser. D., 62, 1872–1884, https://doi.org/10.1007/s11430-018-9353-x, 2020.

Wang, P., Chen, K., Zhu, S., Wang, P., and Zhang, H.: Severe air pollution events not avoided by reduced anthropogenic activities during COVID-19 outbreak, Resour. Conserv. Recy., 158, http://doi:10.1016/j.resconrec.2020.104814, 2020.

Zheng, B., Tong, D., Li, M., Liu, F., Hong, C., Geng, G., Li, H., Li, X., Peng, L., Qi, J., Yan, L., Zhang, Y., Zhao, H., Zheng, Y., He, K., and Zhang, Q.: Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions, Atmos. Chem. Phys., 18, 14095-14111, 2018

Revision:

Lines 110-112: As mentioned above, we aimed to examine the impact of the COVID-19 quarantines on $PM_{2.5}$ over the February 2017 level basing on an observational-numerical hybrid method. The observed $PM_{2.5}$ difference in February 2020 (PMd_{OBS}) was linearly decomposed into three parts: the impacts of changing meteorology (PMd_M), expected routine emissions reductions (PMd_R) and COVID-19 quarantines (PMd_C), which was a reasonable approximation……

Lines 263-267: Furthermore, during the calculation process, the observed $PM_{2.5}$ difference in February 2020 was linearly decomposed into three parts. Although this linear decomposition was reasonable in china in the past few years, we must note that this approximation was lack of considering the meteorology-emission interactions, the product of the emission, the loss lifetime and particularly the sulfate-nitrate-ammonia thermodynamics (Cai et al., 2017), which brought some uncertainties.

Line 98-99 Please give a detailed calculation method of calculating the percentages of PM2.5 changes due to meteorological conditions.

Reply:

We use the **simulated $PM_{2.5}$ data** driven by changing meteorology with two fixed-emissions (1985 and 2010). This percentage is the **difference of simulated $PM_{2.5}$ between each year and 2017** under the same emission scenario **divided by the simulated $PM_{2.5}$ in 2017**. We have added this detailed description in the text.

Revision:

Lines 120-121: This percentage was the difference of simulated $PM_{2.5}$ between each year and 2017 under the same emission scenario divided by the simulated $PM_{2.5}$ in 2017.

Line 110 The author performed linear extrapolation to obtain PMdR in 2020. The reason to use linear extrapolation here is that the emission reduction caused by the policy is linear, or that the PM2.5 decline caused by emission reduction is approximate linear based on the calculated value of PMdR from 2015 to 2019? The calculated extrapolation results in 2020 are compared with others studies in the latter part of the paper, but please analyze the uncertainty of using this method itself.

Reply:

From 2013 to 2019, **the impacts of emission reduction on $PM_{2.5}$** in China were **approximatively linear**, which might due to the control measures in China were particularly enhanced and reinforced. This linear approximation was **employed even by national assessments** aimed to evaluate the effects of *Action Plan of Air Pollution Prevention and Control* from 2013 to 2017 (Geng et al. 2020; Wang et al. 2020).

(1) Due to the implementation of clean air action, control measures have been enhanced and reinforced in China, showing a strong emission reduction signal. Therefore, **the pollutant reduction caused by emission reduction** in China from 2013 to 2019 **was linear**, which might be related to the huge emission reduction. The link has a lot to do with the intensity of emissions reduction. Because the signal of emissions reduction in China had been particularly strong since 2013, it could **be easily detected and showed a linear reduction**.

(2) **The effect of emission reduction on $PM_{2.5}$** in February 2020 was calculated as the change of $PM_{2.5}$ caused by **expected** routine emission reduction, which did not actually happen, but merely gave an assessment of the change of $PM_{2.5}$ caused by emission reduction in the case of "if no COVID-19"**.** Under this hypothetical assessment, **the linear change was still tenable**.

(3) Furthermore, what we emphasize more was **the effect of total emission reduction (**$PMd_R + PMd_C$**)**, that was, the common utility of expected routine emissions reductions and COVID-19 quarantines. This quantity was obtained after excluding the effect of meteorological conditions, **which was completely unaffected by linear extrapolation of emission reduction.**

(4) The calculated extrapolation results in 2020 is consistent with others observational and numerical studies, but we must note that it is still **conjectures rather than true values**, which was lack of considering the meteorology-emission interactions and the sulfate-nitrate-ammonia thermodynamics, which brought some uncertainties. We have added **the analyze of this uncertainty** in line 267.

Revision:

Lines 130-137: According to many previous studies, the change in emissions resulted in a linear change in air pollution in China from 2013-2019 (Wang et al., 2020; Geng et al., 2020) which might be related to the huge emission reduction due to the implementation of clean air action. Because the signal of emissions reduction in China had been particularly strong since 2013, it could be easily detected and the assumption of a linear reduction in pollution caused by emission reduction was applicable in China in the past few years. Based on this approximation, we used the method of extrapolation to speculate the impact of routine emission reduction on $PM_{2.5}$. We performed linear extrapolation based on known PMd_R values from 2015 to 2019 to obtain PMd_R in 2020 (STEP 2, Fig. S3). This PMd_R in 2020 was calculated as the change of $PM_{2.5}$ caused by expected routine emission reduction, which did not actually happen, but merely gave an assessment in the case of "if no COVID-19". Under this hypothetical assessment, the linear change was still tenable.

Lines 265-267: ……we must note that this approximation was lack of considering the meteorology-emission interactions, the product of the emission, the loss lifetime and particularly the sulfate-nitrate-ammonia thermodynamics (Cai et al., 2017), which brought some uncertainties.

Line 145 The changes of circulation field, humidity and wind under stagnant weather are analyzed here. Could you give more details about the specific changes in the weather conditions under these stagnant days? Such as boundary layer height and wind speed?

Reply:

Appreciate for your valuable suggestion. We not only show more **quantitative results**, but also **statistically (with observations and regressions) verified** the percentage of changed $PM_{2.5}$ due to the difference in meteorology between 2017 and 2020. We have **added more quantitative analysis** in the revised presentations.

(1) In February 2020, the correlation coefficients of daily $PM_{2.5}$ and BLH, relative humidity, wind speed and SAT in North China were **-0.63, 0.44, -0.45 and 0.46** respectively, all of which **passed the 95% significance test**. Compared with the climate mean status (February 2017), in February 2020 BLH **decreased by 19.5m (34.5m)**, relative humidity **increased by 5% (10.6%)**, and SAT **rose by 1.6°C (0.9°C)** after detrending, which are conductive to the increase of $PM_{2.5}$ concentration.

(2) We used the meteorological data of boundary layer height, relative humidity, surface temperature and wind speed in February 2017 to establish a multiple linear regression equation to fit $PM_{2.5}$. The correlation coefficients between the fitting results and the actual $PM_{2.5}$ concentration in North China, Yangtze River Delta and Hubei reached 0.84, 0.64 and 0.65, all of which **passed the 99% significance test**. Then, we put the **observed meteorological data in February 2020** into the established multiple regression equation to get the predicted $PM_{2.5}$ concentration. Using the regress-predicted value, the percentage of changed $PM_{2.5}$ due to the difference between in meteorology between 2017 and 2020 were re calculated and is 20.7%, -3.2% and 9.5% in NC, YRD and HB, respectively (the hollow column in Figure S2), **which is consistent with and enhanced the robustness of the results obtained by our**

previous model simulation.

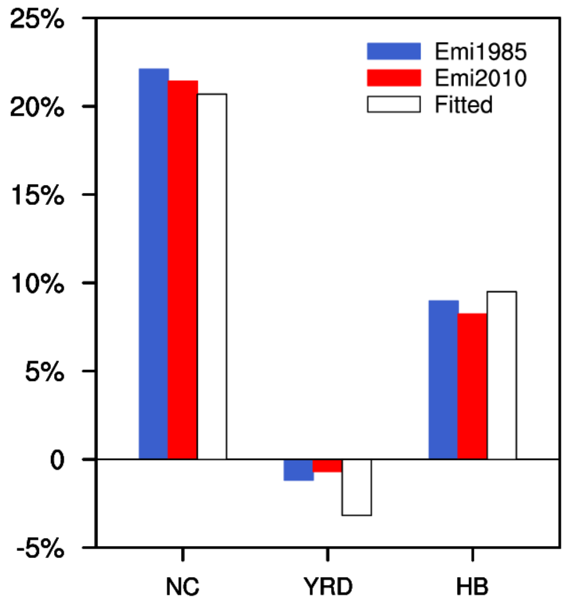

Figure S2. The percentage of changed $PM_{2.5}$ due to the difference in meteorology between 2020 and 2017 by simulated $PM_{2.5}$ with 2010 (red) and 1985 (blue) emission, and regress-fitted $PM_{2.5}$ (hollow). The GEOS-Chem simulations were driven by meteorological conditions in 2017 and 2020 under fixed emissions in 1985 and 2010. The regress-fitted $PM_{2.5}$ was calculated by putting the observed meteorological data in February 2020 into the multiple regression equation fitting $PM_{2.5}$ established by meteorological data in February 2017.

Revision:

Lines 175-186: Compared with the climate (February 2017) monthly mean, boundary layer height (BLH) decreased by 19.5m (34.5m), surface relative humidity (rhum) increased by 5% (10.6%) and surface air temperature (SAT) rose by 1.6°C (0.9°C) after detrending, which were conductive to the increase of $PM_{2.5}$ concentration in February 2020. Furthermore, the correlation coefficients of daily $PM_{2.5}$ and BLH, rhum, wind speed and SAT in North China were -0.63, 0.44, -0.45 and 0.46, respectively, all of which passed the 95% significance test and indicated importance of meteorology. We used the meteorological data in February 2017 to establish a multiple linear regression equation to fit $PM_{2.5}$. The correlation coefficients between the fitting results and the observed $PM_{2.5}$ concentration in NC, YRD and HB reached 0.84, 0.64 and 0.65, exceeding the 99% significance test. Then, we put the observed meteorological data in

February 2020 into this established multiple regression equation to get the predicted $PM_{2.5}$ concentration. Using the regress-predicted value, the percentage of changed $PM_{2.5}$ due to the differences in Meteorology between 2017 and 2020 were re-calculated and is 20.7%, -3.2% and 9.5% in NC, YRD and HB, respectively (Figure S2), which is consistent with and enhanced the robustness of the results obtained by our previous model simulation.

Line 167-170 The results of PMdC showed great differences in the north and south regions. What do you think is the cause of this regional difference? Can you give some explanation?

Reply:

The south of 30N is less polluted than the north region, therefore the **background of basic $PM_{2.5}$ concentration is relatively low (Figure S4a)**. In addition, meteorological conditions in the south in February 2020 **had no positive contribution** relative to that in February 2017, which would not lead to the increase of $PM_{2.5}$ concentration. Both of the above two reasons resulted in **a smaller space for $PM_{2.5}$ decrease**. So the $PM_{2.5}$ concentration that can be reduced by COVID-19 in the south is **not as large as** that in North China, and had regional differences.

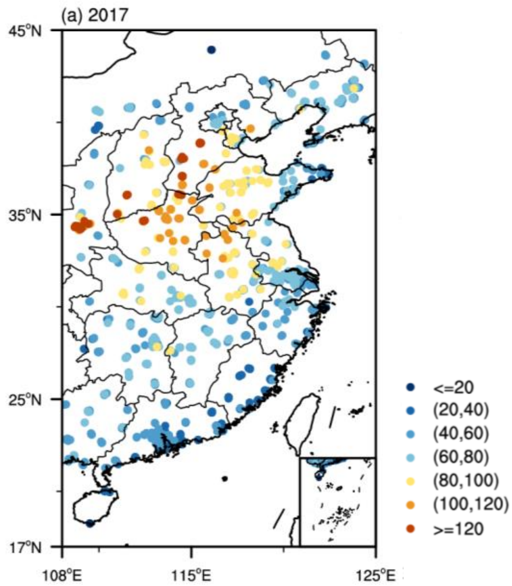

Figure S4a. Observed $PM_{2.5}$ concentrations (unit: μg/m^3) in February 2017.

Revision:

Lines 209-212: Generally, the south region was less polluted than the north, therefore the baseline of $PM_{2.5}$ concentration was relatively lower (Fig. S4a). In addition, meteorological conditions in the south in February 2020 had no positive contribution (Fig. 3a), which would not lead to the increase of $PM_{2.5}$ concentration. These two possible reasons resulted in a smaller space for $PM_{2.5}$ decrease due to COVID-19 quarantines in the south and accompanying regional differences.

Specific comments

Line 98 Please explain "the ratio of PMdM of each year/PMdOBS in 2017" more clearly. Are you sure this is divided by "PMdOBS in 2017" here? Or by observed PM2.5 in 2017?

Reply:

Sorry for this expression error. What we mean here is that to determine the ratio of PMdM of each year/ **observed $PM_{2.5}$ in 2017**, which mean the percentage of changed $PM_{2.5}$ due to the differences in meteorology compared with 2017. This percentage is the difference of simulated $PM_{2.5}$ between each year and 2017 under the same emission scenario divided by the simulated $PM_{2.5}$ in 2017. We have changed the expression to be clearer.

Revision:

Lines 117-120: Simulated $PM_{2.5}$ data driven by changing meteorology with two fixed-emissions (1985 and 2010) were employed to determine the ratio of PMd_M of each year/ observed $PM_{2.5}$ in 2017. Depending on the GEOS-Chem simulations, we found that the percentage of changed $PM_{2.5}$ due to the differences in meteorology remained nearly constant regardless of the emission level (Fig. S2)

Line 101 Keep the same one decimal place.

Reply:

We have made the **corresponding modifications** and have retained a decimal place.

Revision:

Line 122: For example, the percentages due to different meteorology between 2020 and 2017 were 22.1% (21.4%), –1.2% (–0.7%) and 9.0% (8.2%) in NC, YRD and HB under the low (high) emissions (Fig. S2).

Line 103 Please specify which value is multiplied by this percentage.

Reply:

Here we multiply the **2017 observation** by this percentage, and we have changed the expression to be clearer.

Revision:

Lines 125-126: Then, through multiplying the 2017 observation by this percentage, PMd_M can be quantified in each simulation grid with respect to 2017

Line 112 The citation format of this reference is incorrect.

Reply:

We have corrected the citation format of this reference.

Revision:

Line 139: Zhang et al. (2020) also showed that……

Line113 I think it makes more reasonable to write the abbreviation for Beijing-Tian-Hebei here instead of on line 132.

Reply:

We have marked here the abbreviation BTH of Beijing-Tianan-Hebei and have quoted the abbreviation directly later in the paper.

Revision:

Line 139: Zhang et al. (2020) also showed that the emission controls in Beijing-Tianjin-Hebei (BTH) region……

Line 158: Furthermore, Zhang et al. (2020) reported that meteorology contributes 50% and 78% of the wintertime $PM_{2.5}$ reduction between 2017 and 2013 in the BTH and YRD, respectively.

Line 124 The abbreviations for North China here and line 122 are repeated.

Reply:

We have deleted the second repeated abbreviation and referred to the abbreviation directly.

Revision:

Line 151: Relative to the observations in February 2017, negative $PM_{2.5}$ anomalies were centered in NC……

Line 195 Please write NOx here and line 68 in the same way.

Reply:

We have changed NOx into the same way as before.

Revision:

Line 226: Because of break-off transportations, reduced nitrogen oxide (NO_x) increased the concentrations of ozone and nighttime nitrate (NO_3) radical formations.

Figure 1a Clarify what the red and blue bars mean so that the reader can understand this information.

Reply:

The **red bars** indicate an **increase** in existing confirmed cases, and the **blue bars** indicate a **decrease**. We make this significance clear in the caption of Figure 1 (a).

Revision:

Line 414: Figure 1. (a) Variation in existing confirmed cases (bar; red: increase, blue: decrease) and the ratio of accumulated confirmed cases to total confirmed cases (black line) in China…….

Figure 2 Please give the latitude and longitude range of NC, YRD and HB in the figure caption.

Reply:

We select the latitude and longitude range of NC is 32.5-42°N,110-120°E, the range of YRD is 28-32.5°N,118-122°E, and the range of HB is 30-32.5°N,109.5-116°E. We have added the information in the figure caption.

Revision:

Lines 418-419: Figure 2. Differences in the observed $PM_{2.5}$ (unit: $\mu g/m^3$) in February between 2020 and 2017. The black boxes indicate the locations of North China (NC, 32.5-42°N,110-120°E), the Yangtze River Delta (YRD, 28-32.5°N,118-122°E) and Hubei Province (HB, 30-32.5°N,109.5-116°E).

Figure 3 The "due to" after each subheading is repeated, leaving out the last three.

Reply:

We have deleted the repeated "due to".

Revision:

Lines 420-421: Figure 3. $PM_{2.5}$ difference (unit: μg/m^3) in February between 2020 and 2017 due to (a) changing meteorology (PMd_M), (b) expected routine emission reductions (PMd_R), (c) the COVID-19 quarantines (PMd_C), and (d) due to the total emission reduction ($PMd_E = PMd_R + PMd_C$).

Figure 4 Add the units of climate elements in the caption (c) and (d).

Reply:

We have added the units of geopotential potential height at 500 hPa, wind and surface relative humidity in the caption.

Revision:

Lines 426-427: ……including (c) geopotential potential height at 500 hPa (shading; unit: gpm) and its climate mean in February (contour), and (d) wind at 850 hPa (black arrows; unit: m/s), its climate mean (blue arrows) and the increased surface relative humidity (shading; unit: %, stagnant days minus climate mean).

Figure 5 The y-coordinate name is inconsistent with the figure caption.

Reply:

We have corrected the y-coordinate name.

Revision:

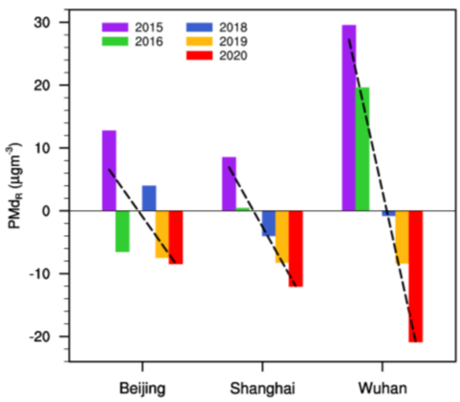

Figure 5. Variation in PMd_R (unit: μg/m^3) with respect to the February 2017 level in Beijing, Shanghai and Wuhan from 2015 to 2019. PMd_R in 2020 was linearly extrapolated from that in the

2015–2019 period. The dotted line is the linear trend.

Figure 6 Add the y-coordinate variable name and unit, just like Figure 5.

Reply:

We have added the y-coordinate variable name and unit in the figure.

Revision:

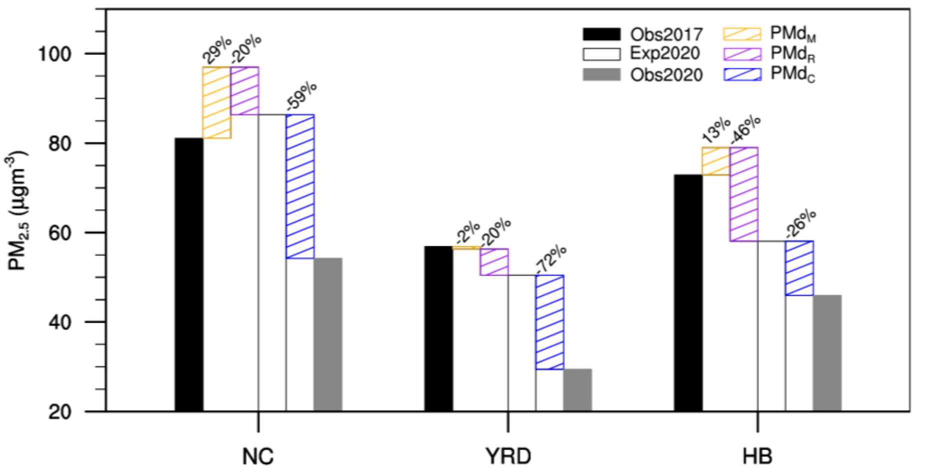

Figure 6. Contributions of PMd$_M$ (orange bars with hatching), PMd$_R$ (purple bars with hatching) and PMd$_C$ (blue bars with hatching) to the change in $PM_{2.5}$ concentration (unit: μg/m^3) between 2020 and 2017 in the three regions. The observed $PM_{2.5}$ concentration in February 2017 (black) and 2020 (gray) was also plotted, and the expected $PM_{2.5}$ concentration without the COVID-19 quarantine is indicated by black hollow bars. The contribution ratios of the three factors (relative to the $PM_{2.5}$ observations in 2020) are also indicated on the corresponding bars.

Figure 7a Change the subtitle "PMd" to "PMdOBS" to maintain consistency of expression.

Reply:

We have changed in the figure.

Revision:

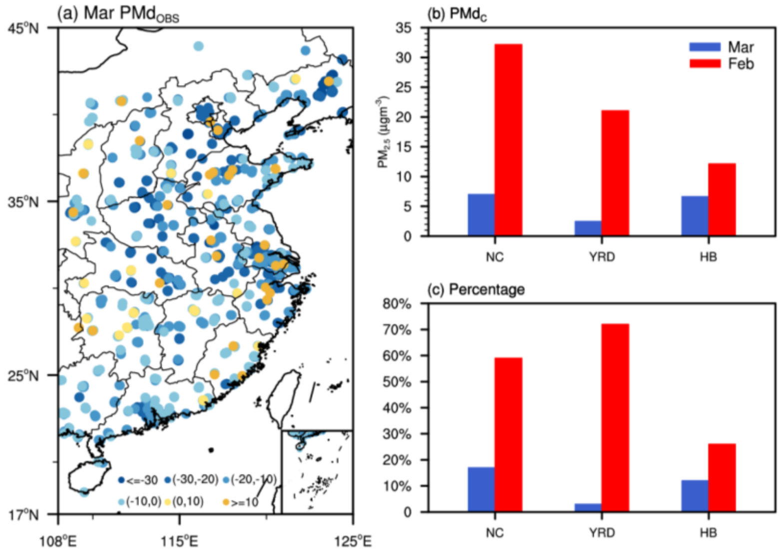

Figure 7. (a) Differences in the observed $PM_{2.5}$ (unit: μg/m^3) in March between 2020 and 2017. (b) Contributions of PMd$_C$ to the change in $PM_{2.5}$ concentration (unit: μg/m^3) between 2020 and 2017 and (c) the contribution ratios of PMd$_C$ (relative to the $PM_{2.5}$ observations in 2020) in March (blue) and February (red) in the three regions.