Point-by-point responses

Journal: Atmospheric Chemistry and Physics

Manuscript ID: acp-2020-903

Title: "Impact of reduced anthropogenic emissions during COVID-19 on air quality in India"

Dear Editor,

Thank you for deciding to accept our paper. We have substantially revised our manuscript after reading all the comments. Our responses are in blue and the modifications in the manuscript are in red.

Comments: L20: clarify what you mean with observed: calculated or measured or both? Clarify what you mean with decreasing rates: I think concentration reductions, correct?

Response: We are sorry for not being clear enough. The significant concentration reductions of $PM_{2.5}$ and its major components are CMAQ model predicted results. Accordingly, we changed "observed" into "predicted" in the revised manuscript. And "decreasing rates" means concentration reductions exactly. We also clarified the meaning in the revised manuscript.

Changes in manuscript:

Abstract (Lines 19-21 in the revision): "Significant reductions of $PM_{2.5}$ concentration and its major components are predicted, especially for secondary inorganic aerosols that are up to 92%, 57%, and 79% for nitrate (NO_3^-), sulfate (SO_4^{2-}), ammonium (NH_4^+), respectively."

Comments: L23: Is this a place give some more detail on which emission reductions where more important (NOx or VOC, and link to the VOC: NOx regimes.

Response: Thanks for the suggestion. We added more explanations about the relative change of NO_x and VOC concentrations and the O_3 sensitive regimes.

Changes in manuscript:

Abstract (Lines 21-23 in the revision): "On average, the MDA8 O_3 also decreases 15% during the lockdown period although it increases sparsely in some VOC-limited urban locations, which is mainly due to the more significant reduction of NO_x than VOCs."

Comments: L88: Please explain in one sentence what these 75 and 50 % QA effectively do, and how many or % datasets are discarded due to this.

Response: We are sorry for not being clear enough. As suggested by TROPOMI (Apituley, 2018), the quality assurance (QA) values (0.75 for NO_2 and 0.5 for HCHO) were used to filter the source data to exclude the interferences such as clouds and snow/ice. As a result, a total of 0.4% and 2.4% NO_2 and HCHO data were removed from our study. We made corresponding changes in the revised manuscript.

Changes in manuscript:

Methodology (Lines 87-89 in the revision): "Besides, we effectively removed the pixels with a QA value less than 0.75 for NO_2 tropospheric column density and 0.5 for HCHO from the datasets to exclude the interferences such as clouds and snow/ice (Apituley, 2018)."

Comments: L121-125: Try to find a more simple way to say which reductions were applied to very polluting, medium polluting, and low polluting industries.

Response: Thanks for the comments. We improved the presentation of industrial emissions reduction calculations. To make it more transparent, we also changed "red, orange, and green industries" into "very polluting (VP), medium polluting (MP), and low polluting (LP) industries." The two tables (Table S4 and Table 1) involved have also been revised accordingly. We made corresponding changes in the revised manuscript.

Changes in manuscript:

Methodology (Lines 114-126 in the revision): "For the industrial sector, we classify the Indian industries into three different classes based on the degree of air pollution caused (https://www.indianmirror.com/indian-industries/environment.html) (Table S4) including very polluting (VP), medium polluting (MP), and low polluting (LP) industries. The Pollution Index (PI) of any industry is a number ranging from 0 to 100, and the increasing value of PI denotes the rising degree of pollution load from the industry. Besides, CPCB, State Pollution Control Boards (SPCBs), and the Ministry of Environment, Forest and Climate Change (MoEFCC) have finalized the criteria on the range of PI for the purpose of categorization of the industrial sector (https://pib.gov.in/newsite/printrelease.aspx?relid=137373) (Table 1).

Based on the above definition of the VP, MP, and LP industry, the emissions before lockdown can be expressed as:

$E_1=N_{VP\text{-}pre}\times S_{VP}+N_{MP\text{-}pre}\times S_{MP}+N_{LP\text{-}pre}\times S_{LP}$, (1)

where S_{VP}, S_{MP}, and S_{LP} are 1, 0.6, and 0.4 as the assigned scores, and $N_{VP\text{-}pre}$, $N_{MP\text{-}pre}$, and $N_{LP\text{-}pre}$ are the number of each category industry during pre-lockdown. Similarly, the emissions during the lockdown are as follows:

$E_2=N_{VP\text{-}lock}\times S_{VP}+N_{MP\text{-}lock}\times S_{MP}+N_{LP\text{-}lock}\times S_{LP}$, (2)

where $N_{VP\text{-}lock}$, $N_{MP\text{-}lock}$, and $N_{LP\text{-}lock}$ are the number of functioning industries during the lockdown."

Comments: L141: Either define here what you mean with acceptable or rather not mention this. Later you mention 2 % for GE/EWS.

Response: Thanks for pointing out this. We deleted the inaccurate statements in the revised manuscript.

Changes in manuscript:

Results and discussion (Lines 141 in the revision): "In general, the WRF model performance is similar to previous studies in India (Kota et al., 2018)."

Comments: L151: How does EPA (2007) pertain to Indian cities. Needs further explanation.

Response: Thanks for the comments. The $PM_{2.5}$ Criteria from EPA (2007) are commonly used for validating air quality model performance in India, such as Mohan and Gupta (2018), Kota et al. (2018), and so on. We make further explanations in the revised manuscript.

Changes in manuscript:

Results and discussion (Lines 150-153 in the revision): "For $PM_{2.5}$, after excluding some abnormally high values of greater than 300 μg m^{-3}, the averaged mean fractional bias (MFB) (-0.48) and mean fractional error (MFE) (0.61) values in all the five urban cites met the criteria limits of ±0.6 and 0.75 claimed by the EPA (2007). And the recommended criteria are commonly used for validating air quality model performance in the Indian region (Mohan and Gupta, 2018; Kota et al., 2018)."

Comments: L160: summing up of concentrations doesn't give columns- please explain better (equation?).

Response: Thanks for the comments. We added Eq. (4) in the revised manuscript to clarify the calculation of the tropospheric column densities of NO_2 and HCHO.

Changes in manuscript:

Results and discussion (Lines 160-164 in the revision): "The CMAQ predicted vertical column densities (VCD) of tropospheric NO_2 and HCHO were calculated using Eq. (4) (H. J. Eskes, 2020).

$$VCD=\sum_{i=1}^{n} C_i \times H_i \times \alpha \ , \quad (4)$$

where n equals 17 as the number of vertical layers in the model (with the highest layer height of ~10 km), C_i means species concentration (ppm), H_i represents each layer height (m), and α is the coefficient for converting units from ppm to molec cm^{-2}."

Comments: L176: here and at various other spots. Careful use of the word trend. In this case you probably mean a tendency. In other cases you discuss a step-change rather than a trend. Check.

Response: Thanks for pointing out this. In this sentence, we meant a tendency. But elsewhere, there was a misuse of the word trend. We made corresponding changes in the revised manuscript.

Changes in manuscript:

Results and discussion (Lines 191-193 in the revision): "Generally, decreases of key pollutants including particulate matter with an aerodynamic diameter of less than 10 μm (PM_{10}) (-16%), $PM_{2.5}$ (-26%), MDA8 O_3 (-11%), NO_2 (-50%), and sulfur dioxide (SO_2) (-14%) are calculated across India."

Results and discussion (Lines 198-199 in the revision): "However, increases in these key pollutants are found mainly in the northeastern, eastern, and parts of southern India."

Results and discussion (Lines 204 in the revision): "However, increases of $PM_{2.5}$ (~20%) are observed in the far-flung northeastern part of India."

Results and discussion (Lines 205-208 in the revision): "As is shown in Fig. S3, lower $PM_{2.5}$ in urban areas during lockdown (Fig. 4) may be attributed to the decrease of RH and increase of planetary boundary layer (PBL) height, while the decrease of precipitation and WS allows $PM_{2.5}$ to accumulate in some rural areas (Schnell et al., 2018; Le et al., 2020)."

Results and discussion (Lines 212-214 in the revision): "Although significant reductions are found in O_3 precursor emissions throughout India during the lockdown, the MDA8 O_3 has not shown a comparable decrease, which is affected by meteorological conditions such as an increase of temperature and decrease of RH (Fig. S3)."

Conclusion (Lines 307-308 in the revision): "Compared with pre-lockdown, observed $PM_{2.5}$ during the lockdown in Delhi, Mumbai, Chennai, Hyderabad, and Bengaluru shows an overall decrease."

Comments: L185: Interesting to know, but explain how that affects the lockdown which was supposedly everywhere. Was it more stringently implied in Mumbai than elsewhere, it may have an implication for your model assumptions.

Response:

We are sorry for not being clear enough. Though nationwide lockdown was imposed, more stringent lockdown measures were implemented in major cities and the worst-hit areas in India (https://www.hindustantimes.com/india-news/lockdown-5-0-these-13-cities-will-see-stricter-rules-more-monitoring/story-FNB1TTTIwBqgILlvCbhQUO.html). Besides, more strict lockdown measures were supposed to be implemented in Mumbai, which accounted for more than a fifth of infections in India (Mukherjee, 2020).

For our model assumption, we reduced the anthropogenic emissions by emission sources during the lockdown, not by regions. Mumbai was significantly affected due to its high industrialization with large emissions reduction in industrial and transportation emission sources. We made more corresponding explanations in the revised manuscript.

Changes in manuscript:

Results and discussion (Lines 187-190 in the revision): "This could be caused by a much larger reduction in emissions as Mumbai and Chennai with high urbanization and industrialization are the most affected areas. In specific, more stringent lockdown measures may be implemented in Mumbai than we assumed, which accounted for more than a fifth of infections in India (Mukherjee, 2020). "

Comments: L187: carefully check whether you really mean a decreasing trend- i.e. a trend that is getting less...Is it a trend at all?

Response: Thanks for pointing out this. The results only showed a decrease, not a decreasing trend. We made corresponding changes in the revised manuscript.

Changes in manuscript:

Results and discussion (Lines 191-193 in the revision): "Generally, decreases of key pollutants including particulate matter with an aerodynamic diameter of less than 10 μm (PM_{10}) (-16%), $PM_{2.5}$ (-26%), MDA8 O_3 (-11%), NO_2 (-50%), and sulfur dioxide (SO_2) (-14%) are calculated across India."

Comments: L201: attribute=>be attributed.

Response: Thanks for the comments. The corresponding changes have been made in the revised manuscript.

Changes in manuscript:

Results and discussion (Lines 205-208 in the revision): "As is shown in Fig. S3, lower $PM_{2.5}$ in urban areas during lockdown (Fig. 4) may be attributed to the decrease of RH and increase of planetary boundary layer (PBL) height, while the decrease of precipitation and WS allows $PM_{2.5}$ to accumulate in some rural areas (Schnell et al., 2018; Le et al., 2020)."

Comments: L209: decreasing trends? Just decreases?

Response: Thanks for the comments. We meant just decreases here. The corresponding changes have been made in the revised manuscript.

Changes in manuscript:

Results and discussion (Lines 212-214 in the revision): "Although significant reductions are found in O_3 precursor emissions throughout India during the lockdown, the MDA8 O_3 has not shown a comparable decrease, which is affected by meteorological conditions such as an increase of temperature and decrease of RH (Fig. S3)."

Comments: L216: duration of the lockdown+> effective implementation of the lockdown?

Response: We are sorry for not being clear enough. In our study, the comparison of the lockdown duration with previous studies aimed to explain the difference between our results and those of previous studies such as Chauhan and Singh (2020), Mahato et al. (2020), and Kumari and Toshniwal (2020). Besides, the lockdown duration can indicate the effectiveness of the lockdown to some extent because there was a relaxation period in the later lockdown (after April 15, 2020), when traffic flow increased (Kumar, 2020). The relaxation period was included in our study, which led to less $PM_{2.5}$ reduction than the previous studies that mainly focused on the first phase of lockdown (from March 24, 2020 to April 15, 2020).

Changes in manuscript:

Results and discussion (Lines 221-223 in the revision): "These differences may be caused by the considered duration of lockdown period. The later lockdown period (after April 15, 2020) is concerned

in our study when there is an increase in traffic flow and some relaxation of lockdown measures (Kumar, 2020)."

Comments: L225: improve English

Response: Thanks for the comments. We improved the corresponding statement in the revised manuscript.

Changes in manuscript:

Results and discussion (Lines 230-231 in the revision): "There are significant changes of $PM_{2.5}$ between the lockdown and pre-lockdown periods. Moreover, we directly quantify the change in $PM_{2.5}$ during the lockdown."

Comments: L229: are lower...

Response: Thanks for the comments. The corresponding changes have been made in the revised manuscript.

Changes in manuscript:

Results and discussion (Lines 235-236 in the revision): "Primary components of $PM_{2.5}$ (EC and POA) are lowered by an average of 37% and 14%, respectively."

Comments: L269: this sentence needs a better explanation. You want to demonstrate that HCHO is a good proxy in the model for overall VOC, and it can be observed as well...

Response: Thanks for the comments. HCHO is used as a proxy for the total VOCs in accordance with previous studies such as Palmer et al. (2003). Previous studies claimed that HCHO is one of the major contributors to total VOCs reactivity (Zhang et al., 2012; Steiner et al., 2008). Besides, HCHO has a strong correlation with VOC (R^2 up to 0.93) and performed well when validated by comparing with satellite-observed data. We made more corresponding explanations in the revised manuscript.

Changes in manuscript:

Results and discussion (Lines 273-276 in the revision): "We investigated the changes of MDA8 O_3 and its major precursors NO_x and HCHO during the lockdown period. HCHO is one of the major contributors to total VOCs reactivity (Zhang et al., 2012; Steiner et al., 2008). It also has a strong correlation with VOC (R^2 up to 0.93) (Fig. S4) and performs well when validated by comparing with

satellite-observed data. As a result, HCHO is used as a good proxy in the model for the total VOCs, consistent with previous studies such as Palmer et al. (2003)."

Comments: L275-280: this is interesting, but it is not clear if you are suggesting that this is important or not in understanding results.

Response: Thanks for the comments. We added more corresponding explanations about the influence of O_3 production sensitivity on its concentration during the lockdown. The change of O_3 production sensitivity regimes during lockdown played an important role in the change in MDA8 O_3 concentration in India. The large reduction of NO_x led to a decrease in MDA8 O_3 in most Indian regions that are NO_x-limited. While the rise of MDA8 O_3 (averaged 5% and up to 21%) was found sporadically in the VOC-limited areas in which more significant decreases of NO_x (compared with VOCs) reduce the O_3 consumption ($NO + O_3 = NO_2 + O_2$) and enhance HO_x concentrations result in an increase in O_3 levels. Also, the increase in O_3 was amplified regionally by the expansion of the VOC-limited zone during the lockdown.

Changes in manuscript:

Results and discussion (Lines 284-292 in the revision): "Besides, $O_3/NO_y < 6$ indicates that O_3 formation is VOC-limited, $O_3/NO_y > 8$ indicates NO_x-limited, and intermediate values are transitional. In India, NO_x-limited regimes are found in vast areas from both Case 1 and Case 2, which was also reported in previous studies (Mahajan et al., 2015). As a result, the large reduction of NO_x leads to decreased MDA8 O_3 in most Indian regions. Compared to Case 1, the VOC-limited area expands mainly in the northwest and south of India from Case 2 during the lockdown. Simultaneously, the rise of MDA8 O_3 (averaged 5% and up to 21%) is found sporadically in these VOC-limited areas in which more significant decreases of NO_x (compared with VOCs) reduce the O_3 consumption ($NO + O_3 = NO_2 + O_2$) and enhance HO_x concentrations result in an increase in O_3 levels. It may also indicate that the increase in O_3 is amplified regionally by the expansion of the VOC-limited regimes due to the lockdown."

Comments: L302: Please clarify this sentence. You are not comparing pre-lockdown with lockdown, but the emissions scenarios. Correct? Please give a quantification of the importance of meteorology and emission in determining the change.

Response: Thanks for the comments. In this sentence, we were comparing pre-lockdown (Case 1) with lockdown (Case 2) to explore the comprehensive effects of meteorology and emissions on the air quality.

The increases of O_3 and other key pollutants in some areas show the important role of various meteorological conditions, which has been discussed in Section 3.2 in the manuscript. The comparison of pre-lockdown (Case 1) with lockdown (Case 1) can determine the effects of variation of meteorology on air quality. For example, it can be concluded that the rise of MDA8 O_3 in some areas is affected by the increase in temperature (4.1K) (Fig. 4 & Fig. 7 in the manuscript).

However, in a high polluted country like India, the lockdown provides a valuable opportunity to assess air pollutants' changes with significantly reduced anthropogenic emissions in a short time. Our study mainly wants to quantify the change in air quality due to the reduced anthropogenic emissions during the lockdown by comparing Case 1 (without emission reductions) and Case 2 (with emission reductions). Consequently, we didn't add more meteorology impacts analysis in the revision. The specific changes in primary and secondary pollutants can tell the effects of emission reduction on air quality across India, such as a decrease of 15% in MDA8 O_3 (Case 2 - Case 1). The corresponding changes have been made in the revised manuscript.

Changes in manuscript:

Conclusion (Lines 307-308 in the revision): "Compared with pre-lockdown, observed $PM_{2.5}$ during the lockdown in Delhi, Mumbai, Chennai, Hyderabad, and Bengaluru shows an overall decrease."

Conclusion (Lines 312 in the revision): "Besides, it can be concluded that the synergetic impact from the meteorological conditions and anthropogenic emissions plays an important role in those increases from pre-lockdown to lockdown."

Reference

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