### **Response to Reviewer**

### Dear referee,

We would like to thank you very much for your professional comments on our manuscript "Impacts of urbanization on air quality and related health risks in a city with complex terrain" (egusphere-2022-486). According to these comments, we have carefully revised the manuscript again. Here are point-by-point responses (in blue color), and the changes are reflected in the revised manuscript (in red color). The line numbers in the authors' responses are obtained from the revised manuscript, in which all the revisions have been accepted.

I appreciate the work that the authors have put into revising the manuscript and responding to my previous comments. I think the paper has greatly improved as a result of the additional figures that show now the previously only hinted at connections between the boundary-layer height or the surface temperature and the changes in pollutant concentrations. I think it is also great that the authors decided to show only two time steps in the main figures and instead increased the size of the subfigures.

*Response:* We are grateful for the positive evaluation and constructive comments on our manuscript. When reading through the paper, I noticed a few additional, but very minor, points, which the authors may want to address before final publication. The line numbers in my comments refer to the revised version without track changes.

We appreciate your time and effort to improve the quality of our manuscript. We have addressed each comment in detail and the responses are listed below.

# **Specific comments**

 You mentioned in response to one of my previous comments that you cut the anthropogenic emission data from the MEIC inventory by about 20%. I think this is important information that should also be included in the paper.

*Response:* We agree with you. In the Section 2.2 WRF-Chem model and experimental designs, we add a note as follows: "*It should be noted that we empirically cut the PM*<sub>2.5</sub> *emissions by about 20% to avoid overestimation of PM*<sub>2.5</sub> *in the model.*". Please see lines 159–160 for details.

2) line 24: 95% CI is not defined in the abstract.

*Response:* Thanks for the constructive comment. We have added the definition of 95% CI to the revised abstract. Please see line 24 for details.

 Line 26ff: "The results show that urban land use led to an increase ... compared to cropland, which was conducive ..."

*Response:* Thanks for the constructive comment. This sentence is revised as "*The results show that urban land use led to an increase in air temperature and the boundary layer height compared to cropland*, which was conducive to the diffusion of  $PM_{2.5}$ .". Please see lines 26–28 in the revised abstract.

 line 113: I would say you are investigating "the impacts of urbanization on air pollutant concentrations" rather than "on air pollutants" themselves. Similar on line 116.

*Response:* We agree with you and "air pollutants" has been replaced by "air pollutant concentrations" in the revised manuscript. The revised sentence is "*In this study, we investigate the impacts of urbanization on air pollutant concentrations and the corresponding health risks in Chengdu.*" (lines 113–114). Similar on lines 116–117.

 line 135: You may want to say "the urban hourly pollutant concentrations reported in this paper" to make it clear that this is not some standard parameter.

*Response:* Thanks for the clarification. The revised sentence is "*There are eight air quality stations* throughout Chengdu, and the urban hourly pollutant concentrations **reported in this paper** are the average results of measurements at all monitoring sites.". Please see lines 135–137 for details.

# 6) Line 141: "10-m wind direction"

*Response:* We are sorry for this mistake. "10-m direction" has been corrected to "10-m wind direction" in line 141 of the revised manuscript.

7) Table 3: I am still confused about the units of  $\beta$ . In Table 3, the units are given as %, but the text says that it is "the percent change of mortality per 10 µg m<sup>-3</sup> increase ...", i.e., the units

would be "%  $(10 \ \mu g \ m^{-3})^{-1}$ .

*Response:* Thanks for the constructive comment. We delete the unit of  $\beta$  from Table 3. Instead, we directly give the meaning of  $\beta$  in the note to Table 3, that is, " $\beta$  *is expressed as the percentage increase (posterior mean and 95% confidence intervals) in daily mortality associated with a 10 µg m<sup>-3</sup> increase in daily PM<sub>2.5</sub>/MDA8 O<sub>3</sub> concentrations." (lines 214–215). We hope this will help readers understand \beta.* 

Fig 3 caption: Please add the subfigure labels to the caption: "attributable to (a) PM<sub>2.5</sub> and (b) O<sub>3</sub>"

*Response:* Thanks for the constructive comment. The revised caption of Figure 3 is "*Premature* mortality from ANAC, CVD, RD and COPD attributable to (a) PM<sub>2.5</sub> and (b) O<sub>3</sub> in Chengdu from 2015 to 2021. The dots represent the mean estimate, and the whiskers represent 95% confidence intervals.". Please see lines 261–263 for details.

9) Line 266: Do you mean "dispersion" instead of "elimination"?

*Response:* Yes, it is "dispersion" instead of "elimination". The complete sentence is "*However, the westerly winds were blocked by the Tibetan Plateau and thereby the* **dispersion** of *PM*<sub>2.5</sub> was limited." Please see lines 271–272 for details.

10) Line 268: I guess you mean "inversion layer" instead of "inverse layer"? The temperature observations, however, do not show a temperature inversion if I connect the dots, i.e., the temperature is not increasing with height. This may be a result of the really coarse vertical resolution with only 6 data points. When I looked up the soundings at weather.uwya.edu, I noticed that the soundings contain actually more data points. Why did you not use the full resolution? If it is because of the computation of the monthly mean, you could first interpolate the soundings to a common vertical grid and then average. I think the comparison of the model with the soundings would really profit from a better vertical resolution. Coming back to the term "inversion" layer, which really means an increase in temperature with height and not just a stable layer, even the mean model profile shows only a more or less isothermal layer, but not a proper inversion.

*Response:* The pressure levels of the sounding data vary from day to day except at a few specific pressure levels (925 hPa, 850 hPa, 700 hPa, 500hPa, 400 hPa, 300 hPa and 250 hPa). Therefore, we have previously only given monthly mean results for these specific pressure layers. Thanks for your suggestion. In the revised manuscript, we supplementarily calculate the monthly mean between these specific pressure layers and finally obtain data for 14 pressure layers. These 14 pressure layers are ~950 hPa, 925 hPa, ~885 hPa, 850 hPa, ~765 hPa, 700 hPa, ~620 hPa, 500 hPa, ~450 hPa, 400 hPa, ~350 hPa, 300 hPa, ~275 hPa and 250 hPa. Since the vertical resolution increases, we show the observed profiles with dashed lines instead of dots in revised Figure 4c and 4d. As shown in the revised Figure 4c and 4d (line 279), the temperature inversion layer near 700 hPa is indeed not obvious. Thus, we agree it should be "stable layer" instead of "inversion layer" here. We have corrected this point in the revised manuscript. Please see lines 273–275 for details.

 Fig. 4: I would suggest to remove the black dots if they have no meaning, because they cause only confusion otherwise.

*Response:* Thanks for the constructive comment. The black dots have been removed from the revised Figure 4c, 4d, 5c and 5d. Please see line 279 for Figure 4c and 4d, line 297 for Figure 5c and 5d.

12) Line 285: Do you mean Figure 6b instead of 5b?

*Response:* We are sorry for this mistake. "Figure 5b" has been corrected to "Figure 6b" in line 291 of the revised manuscript.

13) Figure 6: I really appreciate the authors' attempt to include wind direction in the figure following my previous comment. However, I am afraid the solution with wind barbs is suboptimal as it is almost impossible to see the individual barbs. It might be better to simple plot time series of both wind speed and direction.

*Response:* Thanks for the constructive comment. We remove the wind barbs and present the time series of 10-m wind speed ( $WS_{10}$ ) and 10-m wind direction ( $WD_{10}$ ) in the revised Figure 6. Since  $WD_{10}$  does not change continuously, we use cyan dots to represent the simulated  $WD_{10}$  for aesthetics. As shown in Figure 6 (line 331), the frequency of calm wind is high due to the starting speed of the

anemometer (typically 0.5-1 m/s). In this case, the simulated wind speed must be greater than the observed one, resulting in an overestimation of the simulated WS<sub>10</sub>. Except for the case of calm wind, our model can generally capture the shift in WD<sub>10</sub> during the study period. Therefore, the modeling results of 10-m wind are reasonable and acceptable.

- 14) Section 3.3.2 and Fig. 6: Just a comment: One point that may also affect the comparison between the model and the observations (negatively) is the height difference. The model results are from the first model level, whereas the temperature observations are at 2 m above ground. *Response:* We agree that observations and simulations at different altitudes affect the results of their comparisons. 2-m air temperature (T<sub>2</sub>) and O<sub>3</sub> concentrations are state variables and can directly be obtained from the WRF output files. However, 2-m dew point temperature (TD<sub>2</sub>) and 10-m wind are diagnostic variables, which are recommended to be calculated by function wrf\_user\_getvar in NCL (https://www2.mmm.ucar.edu/wrf/OnLineTutorial/Graphics/NCL/NCL\_functions.php). This method will inevitably have some errors.
- 15) Lines 332 and 333: I would suggest to either say "boundary layer depth" instead of "height" or add "above ground" to the heights.

*Response:* Thanks for the constructive comment. We have added "above ground" to the heights. The revised sentences become "*the boundary layer height was only* ~320 *m* **above ground**." (lines 340–341) and "*The daytime atmospheric boundary layer, also known as the convective boundary layer, could develop to* ~1300 *m* **above ground**." (lines 342–343).

16) Lines 339ff: I don't understand the argument. The northeasterly flow would transport PM<sub>2.5</sub> away from the slope, i.e., down the eastern slope (and not lift the air up along the slope), which then leads to the described large downstream spread.

*Response:* Thanks for the constructive comment. You are right. The convergence of westerly mountain wind (blue arrow in Figure R1) and northeasterly wind (magenta arrow in Figure R1) was conducive to the formation of  $PM_{2.5}$  pollution belt (green circle in Figure R1) and its spread to the downstream of Chengdu. In the revised manuscript, we have reformulated these results. Please see lines 346–349 for details.



Figure R1. Horizontal distribution of  $PM_{2.5}$  with wind vectors at the lowest model level at 2:00 LST. Purple pentacle shows the location of Chengdu.

17) Figs. 7 and 8: Subfigure (a) does not have an x axis label (Time).*Response:* Thanks for the constructive comment. We have added the x axis label (Time) to the revised Figure 7a and 8a. Please see lines 354 and 382 for details.

18) Figs. 7 and 8 caption: I think it would be helpful to add the line types to the description of (a), e.g., "... cross sections of PM<sub>2.5</sub> (color shading), potential temperature (purple contour lines), and boundary layer height (thick black contour line) ...". Also, how is the boundary layer height determined? Is it the output from the PBL scheme or did you determine it directly from the model 3D fields?

*Response:* Thanks for the constructive comment. We accept the suggestion and have added the line types to the description of Figure 7a and 8a. The new captions of Figure 7a and 8a are "*Figure 7*. (a) Temporal-vertical cross sections of  $PM_{2.5}$  (color shading), potential temperature (purple contour lines) and boundary layer height (thick black contour line) at Chengdu." (lines 355–356) and "*Figure 8. (a) Temporal-vertical cross sections of O<sub>3</sub> (color shading)*, potential temperature

*(purple contour lines)* and boundary layer height *(thick black contour lines)* at Chengdu." (lines 383–384), respectively.

In this study, planetary boundary layer physics options (bl\_pbl\_physics) used the Mellor-Yamada-Janjic Scheme (MYJ). The MYJ scheme, based on the turbulence kinetic energy (TKE) budget equation, determined the boundary layer height (PBLH) as where the TKE decreases to a prescribed small value ( $0.2 \text{ m}^2 \text{ s}^{-2}$ ). The prognostic equation for TKE is solved by using diagnostic estimation of potential temperature, water vapor variance, and covariances (Tyagi et al., 2018). PBLH is a state variable and is included in WRF output files.

### Reference

- Tyagi, B., Magliulo, V., Finardi, S., Gasbarra, D., Carlucci, P., Toscano, P., Zaldei, A., Riccio, A., Calori, G., and D'Allura, A.: Performance analysis of planetary boundary layer parameterization schemes in WRF modeling set up over southern Italy, Atmosphere, 9, 272, 2018.
- 19) Line 366: Do you mean "... carry O<sub>3</sub>-rich air eastward"?

*Response:* Yes. The revised sentence is "*The nighttime mountain wind could carry rich-O*<sub>3</sub> *air eastward and enhanced O*<sub>3</sub> *concentrations aloft over the eastern slope of the Tibetan Plateau*.". Please see lines 375-376 for details.

20) Line 404: I would suggest to add "compared to cropland" after "induced by urban land use". *Response:* According to the suggestion, the revised sentence is "*Due to the increase in upward air movement and boundary layer height induced by urban land use compared to cropland, like PM*<sub>2.5</sub>, *NO<sub>x</sub> concentrations also decreased near the surface.*". Please see lines 412–414 for details.

21) Line 411: Do you mean "... with the monthly average value increasing by 5.4 ..."? *Response:* Yes. The revised sentence becomes " $O_3$  concentrations would also increase, with the monthly average value increasing by 5.4 µg m<sup>-3</sup> (4.5%) at 14:00 LST.". Please see lines 420–421 for details.

22) Line 464: "with the existence of Chengdu" – I assume you are referring to the urban land use compared to cropland? The text is a bit unclear because anthropogenic emissions are also related to the existence of Chengdu.

*Response:* Yes, we are referring to the urban land use compared to cropland here. We are sorry for this unclear sentence and it has been revised to "the premature mortalities from ANAC, CVD, RD and COPD due to PM<sub>2.5</sub> decreased by 171 (95%CI: 129–200, or about 6.9%), 45 (95%CI: 34–53, or about 6.7%), 22 (95%CI: 16–27, or about 6.5%) and 23 (95%CI: 17–26, or about 6.2%) in January 2017 when Chengdu area was urban land use rather than cropland.". Please see lines 472–475 for details.

23) Fig. 13: I find it somewhat confusing that the legend entries contain the same set of symbols, but with different labels. You could maybe use different colors for the left and right side of the figure.

*Response:* Thanks for the constructive comment. We accept the suggestion and use different colors for the left and right side of the revised Figure 13 to show the differences in premature mortality attributable to  $PM_{2.5}$  (left of the dotted line) and  $O_3$  (right of the dotted line). Please see line 490 for details.

24) Fig. 13 caption: Please explain in the caption what the dots (average?) and the whiskers (95% CI?) are.

*Response:* Thanks for the constructive comment. We have added an explanation of the dots (mean estimate) and the whiskers (95% confidence intervals) to the caption of Figure 13 as well as Figure 3. Please see lines 493–494 for Figure 13, and lines 262–263 for Figure 3.

25) Line 506: Are you again referring to monthly averages, i.e., "monthly averaged surface PM<sub>2.5</sub> concentrations"?

*Response:* Yes. Thanks for the constructive comments. We have added "monthly averaged" before "surface PM<sub>2.5</sub> concentrations" or "MDA8 O<sub>3</sub> concentrations" in the revised conclusions. Please see lines 518 and 521–522 for details.

## Typos

1) Line 22: "the 7-year annual averages"

*Response:* We are sorry for this mistake. "the 7-year annual average" has been corrected to "the 7-year annual averages" in line 22 of the revised manuscript.

2) Throughout the document, ranges are given with a ~ instead of a – (e.g., line 24: 6542~11726) *Response:* We accept your suggestion. In the revised manuscript, the symbol ~ is replaced by – throughout the document.

 Line 28: "could decrease" – You observed this decrease in your simulations, so you don't need to say "could", simply say "decreased". Similar on lines 30 and 34.

*Response:* Thanks for the constructive comment. Throughout the document, including the abstract and the conclusions, the modal auxiliary verbs before specific results are omitted. Please see lines 29, 30 and 34 for examples.

4) Line 93: "During daytime" instead of "During daydurtime"

*Response:* We have corrected this typo to "During daytime" in the revised manuscript. Please see line 93 for details.

 Line 153: Maybe better say "The height of the lowest model level" instead of "The size of the lowest vertical grid"

*Response:* We agree with you and this sentence is clarified as follows: "*The height of the lowest* model level is about 25 m.". Please see lines 153–154 in the revised manuscript.

6) Line 220: "and for  $O_3$  it is" instead of "and it for  $O_3$  is"

*Response:* Thanks for the constructive comment. This sentence is revised as "In China, the annual evaluation criterion for  $PM_{2.5}$  is the annual average concentration, and for  $O_3$  it is the 90<sup>th</sup> percentile of MDA8  $O_3$  concentration.". Please see lines 223–225 in the revised manuscript.

7) Line 224: "PM<sub>2.5</sub> pollution has improved ... O<sub>3</sub> pollution has not" or "PM<sub>2.5</sub> pollution

improved ... O<sub>3</sub> pollution did not"

*Response:* Thanks for the constructive comment. This sentence is corrected as "*This suggests that PM*<sub>2.5</sub> *pollution improved significantly while O*<sub>3</sub> *pollution did not*.". Please see lines 227–228 in the revised manuscript.

8) Line 226: "that is" instead of "that was"

*Response:* Thanks for the constructive comment. In the revised manuscript, we have corrected this typo. Please see line 230 for details.

9) Fig 3 caption: "ANAC" instead of "ANA".

*Response:* Thanks for the constructive comment. In the revised manuscript, we have corrected this typo. Please see line 261 for details.

10) Line 301: "troposphere" instead of "tropospheric atmosphere"

*Response:* We accept your suggestion and this sentence is clarified as follows: "*We first compare* vertical profiles in the model with the sounding data to determine whether the model captures the vertical structure of the **troposphere**.". Please see lines 307–308 in the revised manuscript.

11) Line 308: Remove (0.44) and (0.77) from the sentence, since these numbers are already contained in the main sentence.

*Response:* Thanks for the constructive comment. (0.44) and (0.77) have been removed. The revised sentence is "*The correlation coefficients (COR) of PM*<sub>2.5</sub> and O<sub>3</sub> are 0.44 and 0.77, respectively.". Please see lines 314–315 for details.

12) Line 355: I guess you mean "downward" instead of "downstream".

*Response:* Yes, it is "downward" instead of "downstream". We have corrected this typo. Please see line 364 for details.

13) Lines 465, 498, and 501: "While" is usually used to start a sub-clause, but not a main clause without a sub-clause. You probably mean something like "however" or "on the other hand", e.g., "On the other hand, anthropogenic emissions ...".

*Response:* Thanks for clarifying the usage of "while". These sentences have been clarified as "*On the other hand*, *anthropogenic emissions in Chengdu increased premature mortalities* ..." (lines 475–476), "*However*, *O*<sub>3</sub> *pollution was likely to occur in warm months* ..." (lines 510–511) and "*O*<sub>3</sub> *exhibited strong diurnal variation with* ..." (line 513), respectively.