Responses to Reviewers' Comments on "Impacts of irrigation on ozone and fine particulate matter ($PM_{2.5}$) air quality: Implications for emission control strategies for intensively irrigated regions in China" by Yuan et al. (MS No.: egusphere-2024-1557)

We would like to thank the reviewers for the thoughtful and insightful comments. The manuscript has been revised accordingly, and our point-by-point responses are provided below. The reviewer' comments are *italicized*, our replies are in **blue font**, and our new/modified text cited below is highlighted in **bold**.

Response to Referee # 1

The authors incorporated a dynamic irrigation scheme into a regional climate-air quality coupled model to investigate the impacts of intensive irrigation on air quality in China. They found that irrigation increases the concentrations of PM2.5 but reduces O3 concentration. They further suggested a 20% combined reduction in NH3 and NOx emissions to mitigate the adverse effects of irrigation on PM2.5 air quality based on additional sensitivity experiments. The manuscript was generally well organized and well written. I only have some minor comments/questions.

We thank the reviewer for the very helpful comments. The paper has been revised to address the reviewer's concerns point by point, and all changes are cited and discussed in the responses below.

1. *The physical processes of the irrigation scheme need some further clarifications. In this study, the model checked if irrigation can be triggered at each timestep. Did you mean irrigation will be turned off immediately when the relative soil moisture is above the management allowable deficit (i.e., 60%)? Note that the objective of irrigation is to make the relative soil moisture approach 100% (i.e., eq. 1). Another question: can the irrigation scheme be activated during both daytime and nighttime?*

We thank the reviewer for pointing out the lack of clarity in the original physical description. In our irrigation scheme, irrigation would not be turned off until the estimated irrigation water amount equals zero (i.e., irrigation water is completely applied), and then the model would check if the soil moisture is below management allowable deficit (MAD) in the next timestep. In other words, the model would only check the soil moisture level after one irrigation event has ended. Therefore, during an irrigation event, although the relative soil moisture is above MAD, irrigation will not be stopped and continue to bring the soil moisture back to field capacity (i.e., to make the relative soil moisture approach 100%).

For the second question, we would say yes. The irrigation can be activated during both daytime and nighttime.

We have now added more clarification in the revised manuscript in Line 173-177 as follows:

"In the next timestep, t+Δt, the remaining irrigation amount is:

$$I_{t+\Delta t} = I_t - \mathrm{IR} \quad (5)$$

Irrigation would not be stopped until I is completely applied to the soil surface (i.e., $I_t = 0$). Subsequently, the model would check if irrigation can be triggered again in the next timestep when the previous irrigation event has finished."

2. *The O3 concentrations in the PBL and in the free atmosphere were both reduced due to irrigation. The authors have well analyzed the reasons for the reduction in the PBL. However, it remains unclear why the O3 concentration was also reduced above the PBL. I suggest adding some explanations in this regard.*

The decrease in O_3 concentration above the PBL is primarily attributable to the low temperature (Fig. 6a) and reduction in ozone precursors including NO_x and CO (Fig. 6d, e). This is because ozone formation is sensitive to temperature and the concentrations of precursors above the PBL are generally lower than those in PBL. Low temperatures and concentrations of precursors induced by irrigation would slow down the formation of ozone and thus reduce O_3 concentration above the PBL. We have further explained this in Line 402-404 as follows:

"**On the other hand, the declines in O_3 in both Puyang and Chengdu above the PBL can be attributable to the reductions in temperature (Fig. 6a and Fig. S4a) and concentrations of precursors induced by irrigation (Fig.6d, e and Fig. S4d, e).**"

Response to Referee # 2

General comments

This study performs a model experiment to estimate the impact of irrigation on meteorology in China, and subsequent effects on air pollutant concentrations. The authors implement a new dynamic irrigation scheme in the WRF-GC model, which they show substantially reduces LST biases in heavily irrigated regions of China. They then quantify the impacts of irrigation, which interestingly has a substantial impact on boundary layer meteorology, resulting in increased $PM_{2.5}$ but decreased ozone. They then explore the impacts of reduced emissions in several scenarios, and discuss their trade-offs in the context of climate change and potential future increases in irrigation.

The paper is very well written, and the analysis is performed to a high standard. Most of my comments below are of a minor nature. In general, the methods are described adequately, and the results are comprehensively reported, although there are rather a lot of figures. I highlight below where I believe the paper could benefit from more comparison with measurements. I also believe that the discussion/conclusion could be more tightly written, so the reader could more easily find the key takeaways of the paper.

We thank the reviewer for the very helpful comments. The paper has been revised to address the reviewer's concerns point by point, and all changes are cited and discussed in the responses below.

In addition, we also revised the discussion/conclusions to highlight the novelty of this study so that the reader can more easily find the key takeaways:

"China possesses the largest irrigated area of the world and the expanding irrigated area has driven changes in many aspects of socioeconomic and environmental concerns, including in energy use and its related CO_2 emissions, water resources, terrestrial emissions of pollutants and greenhouse gases (N_2O and CH_4), and regional climate (Yang et al., 2023). All of these would alter regional air quality through influencing emissions, transport and mixing, chemistry and deposition. **To reveal the possible underlying mechanisms, we implemented a new dynamic irrigation scheme into the WRF-GC model, and found that it substantially reduces model biases for LST, topsoil moisture, air temperature, dew point temperature and wind speed in heavily irrigated areas in China. Irrigation substantially shapes boundary layer meteorology by raising RH and cloud cover as well as decreasing T_2 and PBLH, which subsequently lead to an increase by 28 % (12 μg m^{-3}) in $PM_{2.5}$ and a decrease by 6–8 % (3–4 ppb) in surface O_3. Reduced O_3 also alleviates O_3 impacts on human health and crop yields, with MDA8 O_3 and AOT40 decreasing by ~2 % and 6.5 %, respectively, reflecting an additional pathway via which irrigation can promote crop growth.**

The underlying mechanisms for the contrasting changes in $PM_{2.5}$ and O_3 were further examined. The reduction in O_3 is more obvious during nighttime, which is associated with the enhancement of oxidant titration at elevated NO_x concentration. During daytime, in addition to NO_x titration, other mechanisms, such as enhanced O_3 hydrolysis under higher atmospheric water vapor content, slower photochemical reactions due to lower temperature and more extensive cloud cover, and more heterogeneous uptake of HO_2, play additional roles as well. The components of $PM_{2.5}$ show complex sensitivities to meteorological changes. Specifically, irrigation-induced high RH promotes nitrate formation through three major pathways, i.e., NO_2+OH, NO_2 and N_2O_5 hydrolysis. Strong cooling at daytime suppresses the transition of nitrate from the particle to gas phase and thus reduces the nitrate loss. Ammonium is also enhanced through the neutralization of NH_3 with HNO_3, since high RH and low temperature facilitate the partitioning of gases to particles. By contrast, weak atmospheric oxidation capacity due to irrigation suppresses sulfate formation. Another important finding is that both weak dispersion and secondary formation increase nitrate, sulfate, ammonium, SOA and BC by 4 (70 %), 0.6–0.8 (10–20 %), 1.2–1.6 (40 %), 1.2 (12–16 %) and 4 ug m^{-3} (15–20 %), respectively, among which physical processes contribute approximately 15–20 %, whereas secondary chemical formation accounts for ~ 60 % and 10–30 % of the overall increase in nitrate and ammonium, respectively.

In order to alleviate the increase in ammonium nitrate in intensively irrigated areas, we suggest that a 20 % combined reduction in NH_3 and NO_x emissions can effectively offset the negative effects of irrigation on $PM_{2.5}$ nitrate without worsening nighttime O_3 pollution in large city clusters. Meanwhile, the regional average O_3 impacts on human health and crop yields would be greatly alleviated under different emission reduction strategies proposed in this study except for the 50 % NH_3 emission reductions. Therefore, agricultural development, air pollution control and climate change adaptation are closely coupled with each other. The expansion of irrigated areas in China has slowed down since the 1980s and the IWU declines from the mid-1990s to the early 2000s, because of the advancement of irrigation system (Zhou et al., 2020; Han et al., 2020a)."

Specific comments

1. *Some of the figures and much of the results section discusses the modelling results for two specific locations, Puyang and Chengdu. Since the results are reported in detail for these two cities, there should be some justification added for why they were chosen, and why not just report averages over your areas of interest (NCP and SCB)?*

Thank you so much for this question. The reason why we selected these two cities was that they possess the largest irrigated areas (Fig. 1a) and witness the most evident changes in meteorological conditions due to irrigation (Fig. 4), over NCP and SCB, respectively. By analyzing the changes in meteorological conditions and air pollutants in these two cities, we could have a better understanding of the effects of intensively irrigated areas on boundary meteorology and the concentration of air pollutants in the two regions. However, the effects of irrigation might be weak when averaging over the whole regions (NCP or SCB), since some of the grid cells with weak or even no irrigation activity. We have added some description in Line 329-331:

"**To compare the diurnal variations and vertical profiles of the changes in meteorological conditions and air pollutants in intensively irrigated areas, we selected two typical cities, Puyang and Chengdu, which possess the largest irrigation fraction and witness the most evident changes in meteorological conditions in NCP and SCB (Fig. 1a and Fig. 4), respectively**…."

2. *Would it be useful to calculate human/plant health-relevant metrics for O_3 for the sensitivity scenarios? E.g. for Figure 12, it may be useful to add some discussion of how much the key ozone metrics such as MDA8, AOT40 etc. This might help to put your results in context with other studies looking at ozone reduction policies.*

Thank you so much for this great comment. We have calculated MDA8 O_3 and AOT40 and added them in Fig. 12. We found that 20 % combined emission reduction, 50 % combined emission reduction and 50 % NO_x emission reduction are beneficial for mitigating ozone exposure to human health and crop yields in both NCP and SCB. The corresponding discussion is added in Line 491-504:

"Notably, although 50 % combined and individual reductions in NH_3 and NO_x emissions can strongly reduce nitrate and ammonium, the increase in nighttime O_3 due to weakened titration effect in large city clusters including the Beijing-Tianjin-Hebei (BTH) region, Yangtze River delta and Pearl River Delta should be recognized, while the decrease in O_3 dominates the rest of other regions, reflecting nonlinear responses (Fig. S7). **Such nonlinear responses of O_3 have great ramifications for human health and crop yields. To evaluate these, the changes in MDA8 O_3 and AOT40 (accumulated O_3 concentration over a threshold of 40 ppb) in the summer of 2017 were utilized to evaluate the variations in human and crop exposure to O_3 (Fig. 12c, d). Compared to IRR, NOIRR raises MDA8 O_3 by 2.3 % and 0.8 % in NCP and SCB, respectively. The reduction in MDA8 O_3 under 20 %, 50 % combined emission reductions and 50 % NO_x emission reductions along with irrigation relative to IRR substantially exceeds the abovementioned irrigation benefits, except for the slight degradation in MDA8 O_3 in NCP under 20 % combined emission reductions, suggesting the effectiveness of these strategies for O_3 and $PM_{2.5}$ controls. However, only reducing the NH_3 emissions by 50 % may cause unintended consequences, with MDA8 O_3 increasing by 2.3 % and 0.5 % in NCP and SCB, respectively. Similar changes are also seen in AOT40 under different sensitivity experiments, except that the responses of AOT40 to emission reductions are even larger than that of MDA8 O_3. We thus show that irrigation can enhance crop growth not only by alleviating water and heat stresses, but also by reducing O_3 exposure.**"

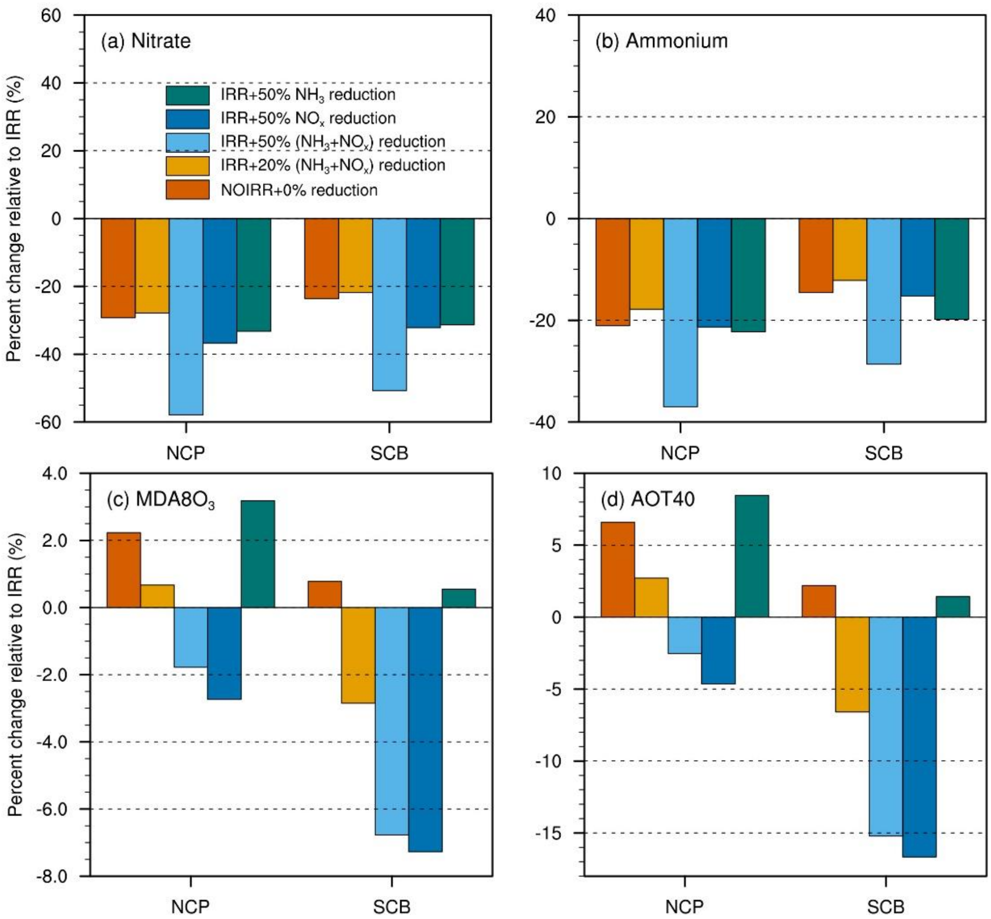

Figure 12. Percentage changes in (a) nitrate and (b) ammonium in response to IRR with a 0, 20,

50 % combined reduction in NH_3 and NO_x emissions, and 50 % individual emission reductions in NH_3 and NO_x, relative to NOIRR, averaged over NCP and SCB during the summer of 2017.

3. *Compare your modelled soil moisture with observations? It would be very useful to know whether the irrigation scheme you implement in WRF-GC is able to achieve realistic soil moisture levels in the NCP and SCB. Since this paper introduces a dynamic irrigation scheme into this model for the first time, it should be evaluated.*

We have compared the simulated soil moisture with the popular soil moisture dataset, Global Land Data Assimilation System (GLDAS), which assimilates many satellite- and ground-based observational data products, using advanced land surface modeling and data assimilation techniques. Generally, the irrigation scheme substantially improves the simulated soil moisture in Henan province and SCB, with the negative bias of –0.1 $m^3 m^{-3}$ being reduced to around –0.06 (~50 % improvement), although there is slight deterioration in northern NCP. We have added the figure below and corresponding description in Line 254-265 as follows:

"We thus compared the simulated LST and soil moisture from IRR and NOIRR with MODIS LST and surface soil moisture from GLDAS, respectively, to quantify the ability of irrigation processes to reduce model biases (Figure 3). The large positive differences of LST between MODIS and NOIRR indicate that the standard WRF-GC model (i.e., without irrigation) overestimates the LST greatly with the biases more than 2 °C in Northeast China, Central China, Southwest China, and parts of South China (Fig. 3a). When irrigation is introduced in the model, such warm biases almost disappear in the intensively irrigated areas including Northeast China, Inner Mongolia, Ningxia, Shaanxi, NCP and SCB (Fig. 3b). **Regarding soil moisture, NOIRR underestimates it by more than 1 $m^3 m^{-3}$ in SCB and 0.06 $m^3 m^{-3}$ in southern NCP (Fig. 3d). With irrigation, IRR narrows the negative biases by more than half in SCB and almost cancels out the negative biases in southern NCP, despite the slight increase in positive biases in northern NCP (Fig. 3e). The largest improvements for simulated LST and soil moisture primarily occur in the southern part of NCP and the whole SCB where the warm and dry biases are reduced by more than 2 °C and 0.06 $m^3 m^{-3}$, respectively,** suggesting that irrigation should be properly represented in numerical models to more accurately simulate meteorological variables in intensively irrigated regions (Yuan et al., 2023).

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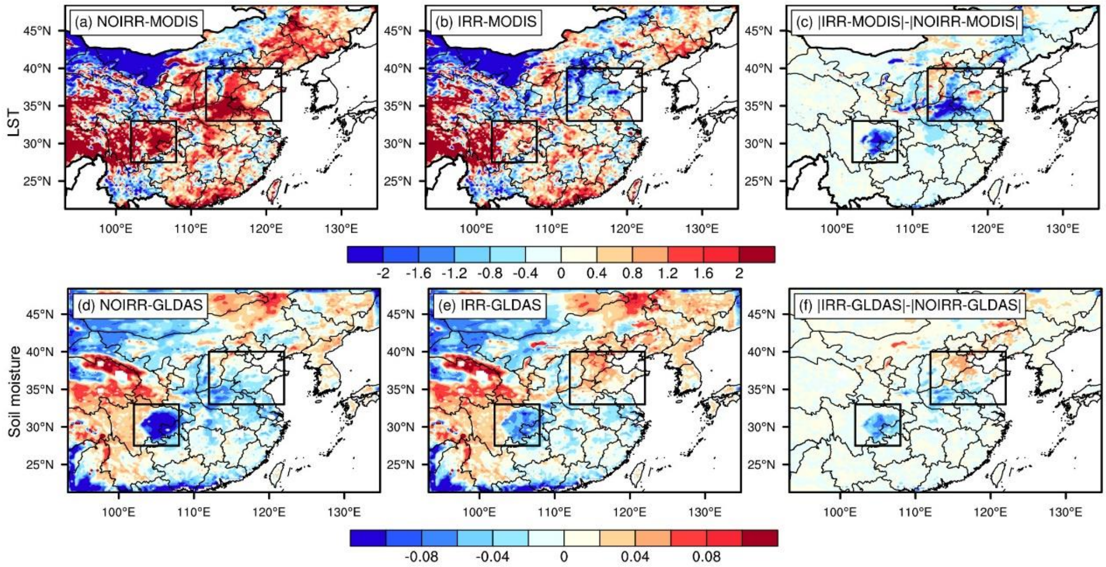

Figure 3. Spatial distribution of the mean differences of (a–c) land surface temperature (LST, °C) and (d–f) surface soil moisture (0–10 cm, m^3 m^{-3}) between (a, d) sensitivity experiment without irrigation (NOIRR) and observations, (b, e) sensitivity experiment with irrigation (IRR) and observations, and (c, f) the differences between (b) and (a) or (d) and (e) during the summer of 2017, which quantitively show how much the irrigation scheme can reduce the NOIRR biases. Negative values denote model improvements, while positive values indicate deterioration. MODIS indicates the LST obtained from the Moderate Resolution Imaging Spectroradiometer, and GLDAS indicates the soil moisture generated from the Global Land Data Assimilation System.

4. *The result that adding irrigation into WRF-GC improves comparison with MODIS LST substantially in heavily irrigated areas is very interesting and maybe deserves to be featured more prominently. It leaves me wondering whether IRR has any decreased biases of T2, windspeed, RH and other meteorological variables in the NCP and SCB. However, I recognise that you evaluate the nudged CTL run rather than the non-nudged IRR run. That being said, it would be useful to contextualise the changes in the aforementioned meteorological variables between the NOIRR and IRR run in the NCP+SCB with comparisons with meteorological observations, and comment on whether including irrigation improves any biases.*

We have compared the simulated meteorological conditions with in situ observations by calculating the relative changes in root mean square error (RMSE) for simulated air temperature (T_2), relative humidity (RH), dew point temperature (T_d) and wind speed when irrigation is introduced. Figure S2 shows the difference and relative changes in the RMSE of these variables between NOIRR and IRR compared with meteorological observations. Irrigation scheme substantially reduces the biases of simulated T_2 and T_d in NOIRR. Irrigation also improves the simulated RH in SCB, but worsens it in NCP. Wind speed is also improved by irrigation with the RMSE decreasing by 6 % in Hebei, Shandong province and the whole SCB, although the improvement in wind speed is the smallest among T_2, T_d and wind speed. Overall, with irrigation, the ability of WRF-GC model to simulate T_2, T_d and wind speed is improved by 30 %, 30 % and 6 %, respectively.

We have added the corresponding description in the aforementioned meteorological variables between the NOIRR and IRR run in Line 311-314:

"… Consequently, including irrigation reduces the root mean square error of NOIRR for T_2, dew point temperature, RH and wind speed by 30 %, 30 %, 30 % and 6 % against observations at each weather station, respectively, particularly in SCB (Fig. S2), undermining the importance of improved representation of agricultural management in regional climate models."

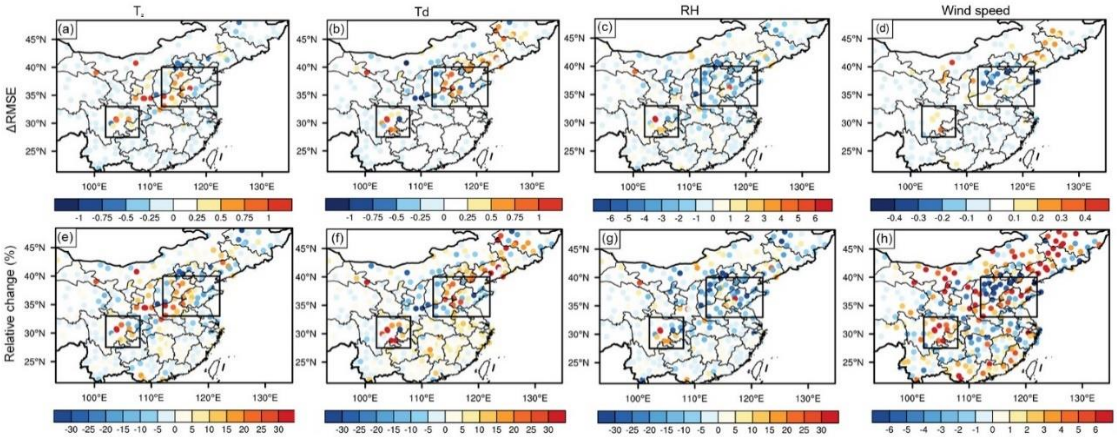

Figure S2. Changes in the root mean square error (ΔRMSE) of (a) air temperature at 2 m (T_2, ℃), (b) dew point temperature (T_d, ℃), (c) relative humidity (RH, %) and (d) wind speed (m s^{-1}) against observations at each station over the model domain in IRR relative to NOIRR, and (e–h) the corresponding relative percentage changes (%). Positive values indicate reductions in RMSE due to irrigation, while negative values indicate increases in RMSE due to irrigation.

5. *On L388, you give percentage change for $PM_{2.5}$ and its components. I think similar relative change percentages should be given throughout the results section (where possible), to help contextualise the changes.*

Thank you for this valuable comment. We have added the relative percentage changes in meteorological conditions along with the specific values in the revised manuscript.

6. *I think in Figure 12 it is confusing to compare the concentrations in the sensitivities to NOIRR rather than to IRR. In the paper, IRR is framed as the most realistic model run, as the point is well made that including a representation of irrigation is necessary for accurately representing meteorology (and therefore chemistry). Therefore, it seems to make more sense to me to compare the sensitivity scenarios with the most realistic representation of the current atmosphere, the IRR scenario.*

We have revised Fig. 12 and compared the concentrations in the sensitivity experiments to IRR as you suggested. The revised Fig. 12 is shown below:

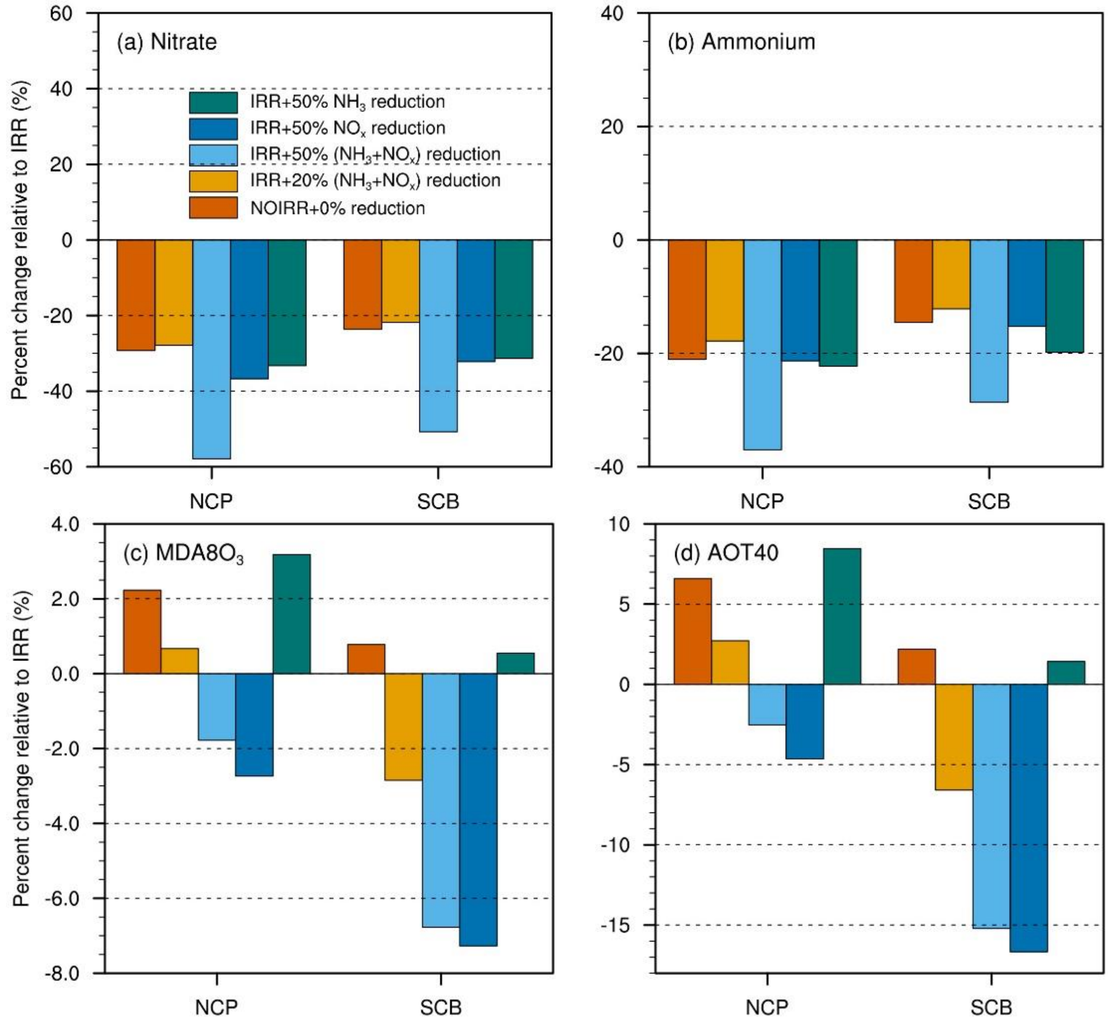

Figure 12. Percentage changes in (a) nitrate and (b) ammonium in response to IRR with 0, 20, 50 % combined emission reductions in NH_3 and NO_x, and 50 % individual emission reductions in NH_3 and NO_x, relative to NOIRR, averaged over NCP and SCB during the summer of 2017.

Technical corrections

7. *L35-6: I think I know what you mean, but referring to ozone as a primary pollutant here is confusing. Also, citing a study to show that PM/ozone is a major cause of avoidable mortality in China here would be useful, e.g. one of the Global Burden of Disease studies.*

Thank you so much for pointing out this. We have revised this sentence and cited two papers which discuss the health burdens caused by surface O_3 and $PM_{2.5}$ in China. The revised sentence in manuscript is shown below:

"Among the various pollutants, fine particulate matter with diameter < 2.5 µm ($PM_{2.5}$) and surface ozone (O_3) are closely associated with increased mortality risks in China (Liang et al., 2019; Wang et al., 2016)"

References:

Liang S, Li, X., Teng, Y., Fu, H., Chen, L., Mao, J., Zhang, H., Gao, S., Sun, Y., Ma, Z., and Azzi, M:

Estimation of health and economic benefits based on ozone exposure level with high spatial-temporal resolution by fusing satellite and station observations. Environ Pollut., 255(Pt 2), 113267. https://doi.org/10.1016/j.envpol.2019.113267, 2019

Wang, J., Xing, J., Mathur, R., Pleim, J.E., Wang, S., Hogrefe, C., Gan, C.M., Wong, D.C., and Hao, J.: Historical trends in PM2.5-related premature mortality during 1990–2010 across the northern hemisphere. Environ. Health Perspect. 125 (3), 400–408, https://doi.org/10.1289/EHP298, 2016.

8. *L37: 106 μg m^{-3} seems high and I can't find it in An et al. (2019). In this paper, Figure 1 seems to show NCP $PM_{2.5}$ reaching a maximum of an annual mean value ~83 μg m^{-3} during 2012.*

We have double-checked the papers and found that the 106 μg m^{-3} is indeed shown in Fig. 1 of Wang et al. (2020) in Beijing-Tianjin-Hebei region. We are sorry about this mistake and have now revised this sentence as follows to make it more readable:

"**The annual $PM_{2.5}$ concentration in the North China Plain (NCP) exhibited a steady increase from 1970 to 2013 based on visibility data (An et al., 2019), with the Beijing-Tianjin-Hebei region recording a peak level of 106 μg m^{-3} in 2013 (Wang et al., 2020)**,"

Reference:

Wang, Y., Gao, W., Wang, S., Song, T., Gong, Z., Ji, D., Wang, L., Liu, Z., Tang, G., Huo, Y., Tian, S., Li, J., Li, M., Yang, Y., Chu, B., Petäjä, T., Kerminen, V.-M., He, H., Hao, J., Kulmala, M., Wang, Y., and Zhang, Y.: Contrasting trends of $PM_{2.5}$ and surface-ozone concentrations in China from 2013 to 2017, Natl. Sci. Rev., 7(8), 1331–1339, https://doi.org/10.1093/nsr/nwaa032, 2020.

9. *L40: Use more specific language than 'high $PM_{2.5}$'. Does this refer to NAAQS or WHO AQGs or something else?*

Thank you so much for this question. It refers to the annual standard of Chinese Ambient Air Quality Standards Grade II, which is 35 μg m^{-3}. We have revised this sentence in the manuscript as follows:

"…more than 65 % of the Chinese people were still exposed to $PM_{2.5}$ **above the standard of Chinese Ambient Air Quality Standards Grade II**, …"

10. *L41: Positive trends rather than upwards?*

Have corrected to "Positive trends" now.

11. *L51: Missing word "During the COVID-19 [pandemic/period/lockdowns/etc.]"*

Have corrected to "During the COVID-19 lockdowns" now.

12. L52: Typo, should be rose not rosed

Done.

13. L56: Maybe [several/multiple/?] instead of "considerable"

Have corrected to "multiple".

14. L76: 'lowers' the PBLH instead of 'thins'? And 'a' coupled model rather than 'the'?

Done.

15. L128: Typo: biogenic not biomass

Done.

16. L208-210: I think the four sensitivity experiments could be more clearly described here.

We have added more detailed description in the manuscript and a Table in the supplementary to show the settings of each experiment.

"The model settings of the four experiments including the irrigation scheme, physical and chemical schemes, spatiotemporal resolutions, as well as natural and anthropogenic emissions, are the same as those of IRR except that the anthropogenic emissions of NO_x and NH_3 were scaled with different ratios to mimic different emission reduction strategies (Table S1): (1) 20 % combined reduction in NO_x and NH_3 emissions (Emiss_20c), (2) 50 % combined reduction in NH_3 and NO_x emissions (Emiss_50c), (3) only 50 % reduction in NO_x emissions (Emiss_50NO$_x$), and (4) only 50 % reduction in NH_3 emissions (Emiss_50NH$_3$). These lie in the fact that previous studies have highlighted the effectiveness of the emission reductions in NH_3 and NO_x in reducing $PM_{2.5}$ pollution in China (Zhai et al., 2021; Liu et al., 2021c)."

Table S1. Design of model experiments

Experiment	Irrigation	Anthropogenic emissions	Aerosol–radiation interaction & Aerosol–cloud interaction	Grid–nudging
CTL	Off	Normal	On	On
NOIRR	Off	Normal	Off	Off
IRR	On	Normal	Off	Off
Emiss_20c	On	NO_x and NH_3 emissions are reduced by 20 %	Off	Off
Emiss_50c	On	NO_x and NH_3 emissions are	Off	Off

		reduced by 50 %		
Emiss_50NO_x	On	NO_x emissions are reduced by 50 %	Off	Off
Emiss_50NH_3	On	NH_3 emissions are reduced by 50 %	Off	Off

17. L243-244: Does the 'default model' refer to CTL? If so, maybe clearer to just use "CTL"

The default model refers to NOIRR which is the standard WRF-GC model without considering irrigation. We have corrected it to "standard WRF-GC model (i.e., without irrigation)" for clarification.

18. L288: would be useful to quantify the relative increase in soil moisture

Yes. We have added the relative percentage change in soil moisture, as shown in Fig, A1, which ranges from 20% to 50%. The revised sentence is below:

"Irrigation increases soil moisture by around 0.04–0.08 m^3 m^{-3} **(20–50 %)** over irrigated areas in NCP and SCB."

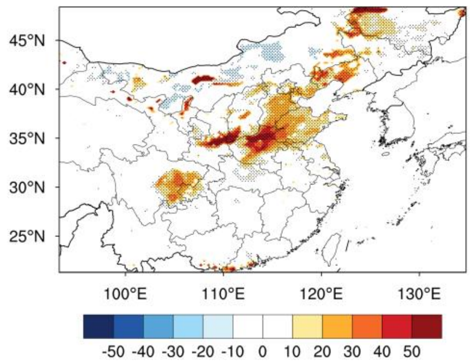

Figure A1. Percentage changes (%) in soil moisture in IRR relative to NOIRR during the summer of 2017.

19. L491: Discussion and Conclusions is maybe a better title for this section?

Done

20. Fig2: The figure caption should make it clear these are seasonal averages

Have corrected the figure captions in Fig. 2 and other figures.

The revised figure caption in Fig. 2 is:

"**Figure 2. Spatial distribution of seasonal average (a–b) air temperature at 2 m (T_2,°C), (c–d)**

surface afternoon (13:00–17:00, Beijing time) ozone (O_3, ppb) and (e–f) fine particulate matter ($PM_{2.5}$, µg m^{-3}) derived from surface observations and control (CTL) experiment during the summer of 2017."

21. *Fig6: The x axis ticklabels could be shown without decimal places to make them easier to read in a, b and f.*

Done. Please see the revised Fig. 6:

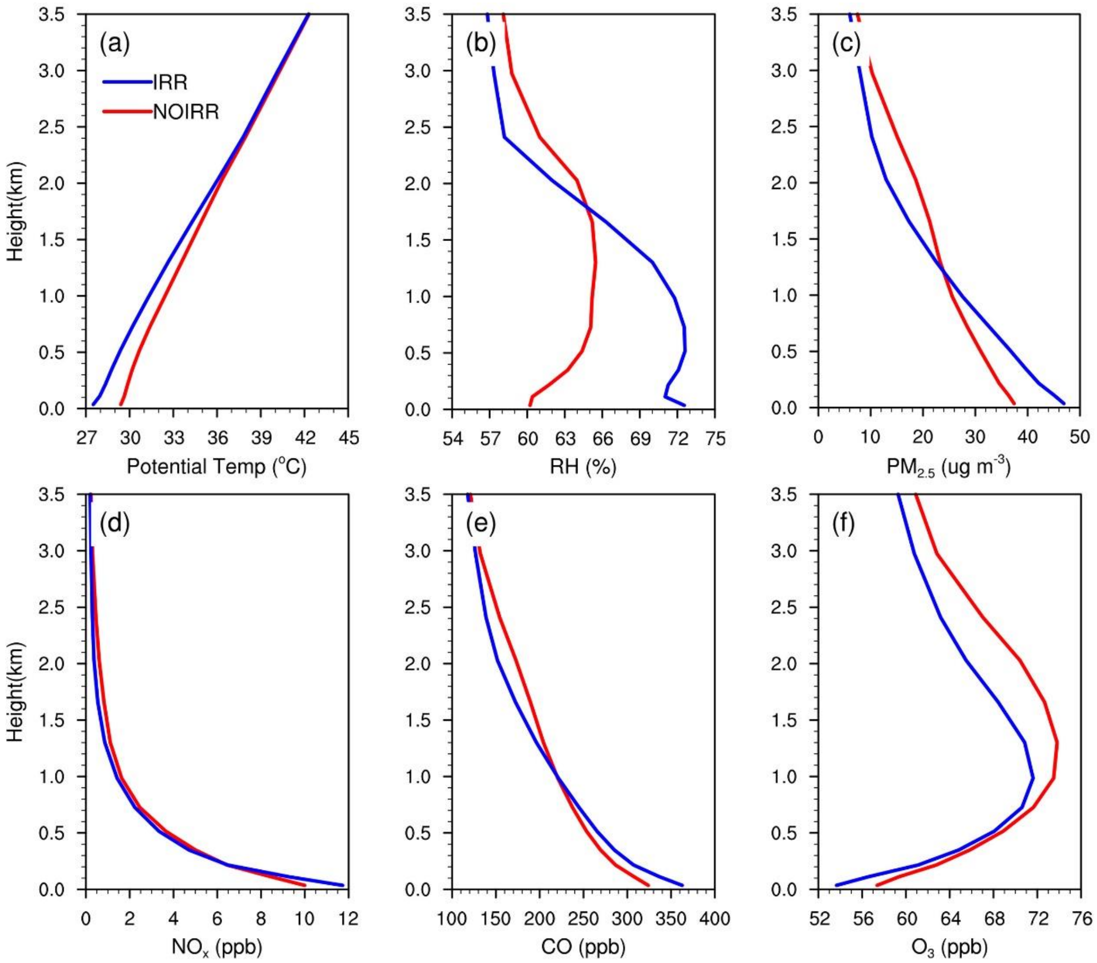

Figure 6. Vertical profiles of daily mean (a) potential temperature (°C), (b) RH (%), (c) $PM_{2.5}$ (µg m^{-3}), NO_x (ppb), CO (ppb) and O_3 (ppb) from IRR and NOIRR in Puyang averaged over the summer of 2017.

22. *Fig13: Please repeat the figure legend from Figure 12. Figures should be comprehensible in isolation.*

Done. Please see the revised Fig. 13:

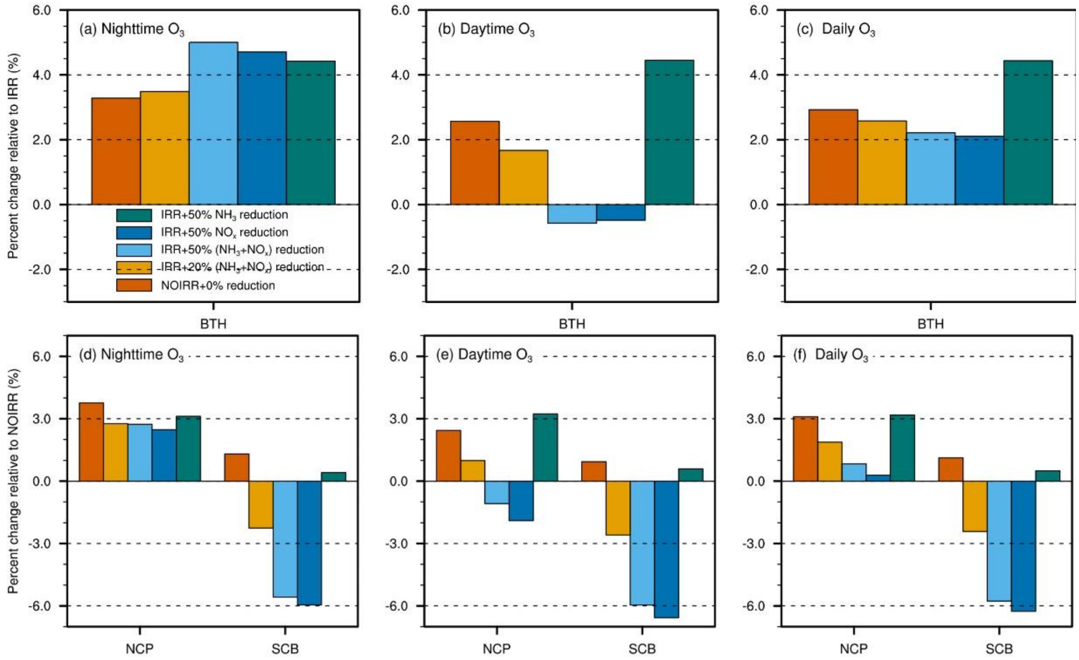

Figure 13. Same as Fig.12 but for nighttime, daytime and daily mean surface O_3 in Beijing-Tianjin-Hebei (BTH), NCP and SCB.

23. *The authors could consider using colourblind friendly colormaps throughout. For example, red-green diverging and rainbow colourbars are not colourblind friendly.*

Thank you very much for the valuable comment and we have replaced the original red-green diverging and rainbow colourmaps with colorblind friendly colormaps for all figures in the revised manuscript.