Response to Comments of Reviewer #1

Manuscript number: acp-2024-3470
Title: Effects of 2010-2045 climate change on ozone levels in China under carbon neutrality scenario: Key meteorological parameters and processes

General comments: The overall manuscript is well-documented, but I have some major concerns and suggestions for improvement:
Thanks to the referee for the helpful comments and constructive suggestions. We have revised the manuscript carefully and the point-to-point responses are listed below.

Major concerns/questions:

1. The title emphasizes the effects of climate change but does not highlight emissions, which have a much higher impact on ozone levels compared to climate change. Since the manuscript examines both, the title should reflect the role of emissions more explicitly.

Response:

This manuscript is focused on the effects of climate change on O_3 levels, with detailed analyses on key meteorological parameters and processes to understand the climate-induced O_3 changes. Although the effects of changes in anthropogenic emissions on O_3 levels are briefly discussed in Section 3.5, these discussions aim only to provide a reference level for the understanding of the magnitude of climate-induced changes in O_3.

As shown in the third paragraph of "Introduction", several papers have already quantified the effects of changes in anthropogenic emissions on O_3 under carbon neutrality scenario (Shi et al., 2021; Xu et al., 2022; Wang et al., 2023). However, none of them examined the effects of future climate change. We feel that the current title can better highlight the novelty of our work.

2. GCAP2.0 is a one-way offline model, and the meteorology you used to drive GEOS-Chem is parameterized. In the "Results" section (e.g., Figure 1), meteorological variables are shown. Are these variables inputs or outputs of the model? Please clarify. Furthermore, it is crucial to clearly define what is considered a climate variable in this study and describe the differences in these variables between present-day and future scenarios, similar to the approach used for emissions (Section 2.2.2). Additionally, since GCAP2.0 is a one-way offline model, do changes in emissions have any feedback effect on meteorology? I assume not, but this should be explicitly addressed.

Response:

GCAP 2.0 model framework, developed by Murray et al. (2021), is a one-way offline coupling between the GISS-E2.1 GCM and the GEOS-Chem model. Meteorology for driving GEOS-Chem model (namely GCAP 2.0 meteorology) is archived from the climate outputs of GISS-E2.1 GCM. Therefore, meteorological variables shown in Figure 1 are outputs of the GISS-E2.1 GCM model.

In this work, we use the 10-yr average of GCAP 2.0 meteorology to represent climatology. The GCAP 2.0 meteorology averaged over 2005-2014 is used to represent the present-day climate (2010), and that averaged over 2040-2049 under SSP1-1.9 scenario is used to represent the future climate (2045). All meteorological variables shown in Figure 1 are climate variables, and their differences between present-day and future (under SSP1-1.9 scenario) are presented in Figure 1 and described in detail in Section 3.1.1.

As discussed above, GCAP 2.0 is a one-way offline coupling between the GISS-E2.1 GCM and the GEOS-Chem model, so changes in emissions have no feedback effect on meteorology.

3. The manuscript frequently discusses regions like EC, NCP, or YRD. Instead of presenting results for all of China, zooming in on these regions while plotting would provide more clarity, particularly for localized changes.

Response:

Following your suggestions, we carefully examined our presentation in the text and all figures, and found that two figures (Figures 2 and 9) are presented in terms of regions such as EC, NCP, or YRD. Figure 2 shows the 2010-2045 changes in seasonal mean meteorological parameters in EC, and their corresponding localized changes can be seen in Figure 1. Figure 9 shows the climate-driven seasonal and annual mean MDA8 O_3 concentration changes projected by MLR model using the climate outputs from GCAP 2.0 and six CMIP6 models under SSP1-1.9 scenario. To see localized changes, we have added Figure S5 (see below) in the Supplementary Material to see the spatial characteristics corresponding to Figure 9. We have also added the following sentences in the second paragraph of Section 3.4 to describe the localized changes: "The spatial distributions of climate-driven changes in annual mean MDA8 O_3 concentrations from GCAP 2.0 and the other six CMIP6 models are shown in Fig. S5. The climate-induced increases in annual mean MDA8 O_3 predicted by all models are mainly concentrated in central and northern EC. In NCP and its surrounding areas, while the maximum increases in annual mean MDA8 O_3 concentrations were simulated to be 2-4 ppbv from GCAP 2.0, the values were 4-8 ppbv from four of the six CMIP6 models.".

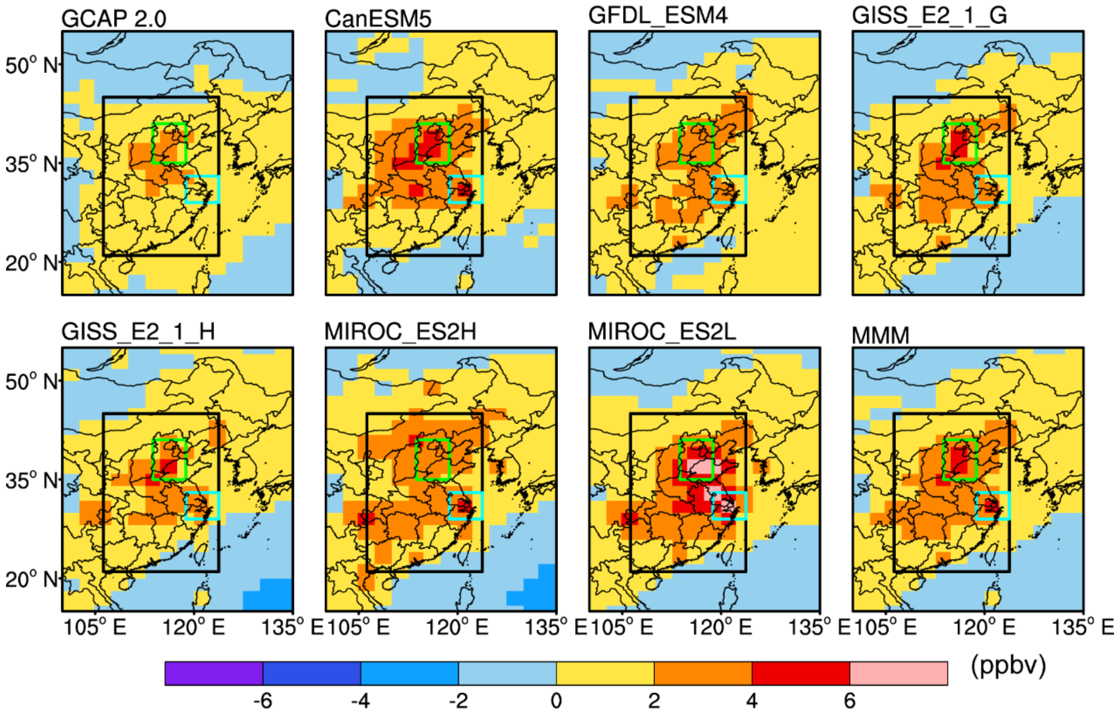

Figure S5. The spatial distributions of climate-driven changes in annual mean MDA8 O_3 concentrations (ppbv) in EC projected by MLR model using the climate outputs from GCAP 2.0 and the other six CMIP6 models under SSP1-1.9 scenario. The multi-model mean (MMM) is calculated from the average of the six CMIP6 models.

4. The model's performance in capturing present-day results (e.g., Figure 3) is concerning. For instance, the MAM R-value is only 0.12, indicating a poor representation of trends. This raises questions about the reliability of future projections. Moreover, your results are at the lower end of CMIP6 model projections. Please provide a detailed explanation of why GCAP behaves differently, even for regional means.

Response:

In MAM, compared with the observations, the GEOS-Chem model has low biases in NCP and YRD (with the NMBs of -24.0% and -6.7%, respectively) but high biases outside these two regions (with a NMB of 9.7%), leading to a low spatial correlation coefficient (R) of 0.12 over the whole of China. The fairly low biases in NCP and YRD in the GEOS-Chem model are not expected to affect our projections of the future changes in MDA8 O_3 concentrations.

Our results are at the lower end of CMIP6 model projections, which can be explained by the differences in key meteorological parameter anomalies between GCAP 2.0 and six CMIP6 models.

For example, as shown in Section 3.3.1, the top two most important meteorological variables over EC in DJF are T2max and SW (Figures 6 and 7), and their corresponding changes over 2010-2045 projected by GCAP 2.0 are 1.3 K and 4.4 W m^{-2} (Figure 2). However, the projected future changes in T2max and SW over 2010-2045 from CMIP6 multi-models are in the range of 1.0-2.1 K and 8.7-11.2 W m^{-2}. Therefore, the underestimation of the increases in T2max and SW in GCAP 2.0 leads to the underestimation of net chemical productions of O_3. As a result, the increases in MDA8 O_3 predicted by GCAP 2.0 are at the lower end of CMIP6 multi-model projections.

5. For difference plots of the same variable, use a consistent color scale to facilitate comparison of magnitudes across different forcing factors. For example, in Figure 4, ensure the scales for "climate," "emissions," and "combined" effects are the same.

Response:

Thanks for the suggestion. We have revised Figure 4 as suggested (see below).

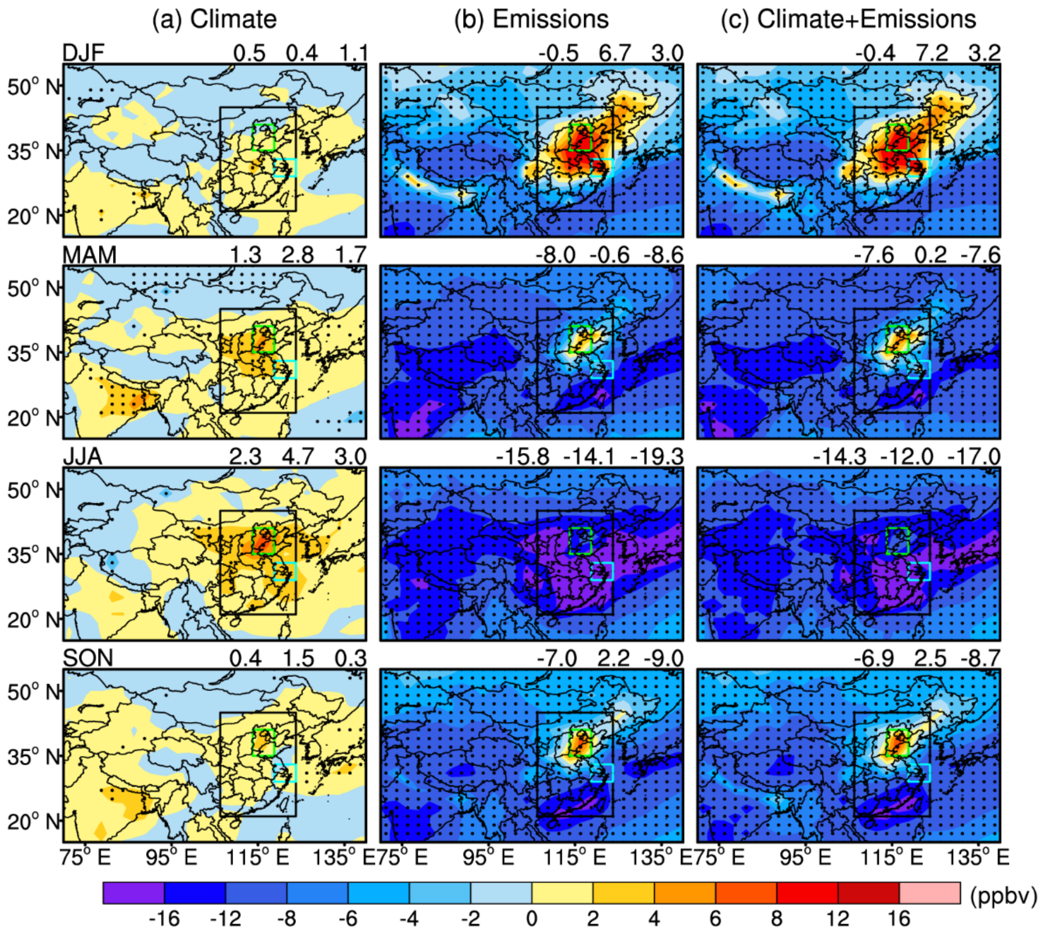

Figure 4. Predicted future changes in seasonal mean MDA8 O_3 concentrations (ppbv) due to (a) climate change alone (CfutEpd minus CpdEpd), (b) emission change alone (CpdEfut minus CpdEpd), and (c) combined climate and emission changes (CfutEfut minus CpdEpd) under SSP1-1.9 scenario. The black, green and blue rectangles indicate the domain of EC, NCP, and YRD, respectively. The dotted areas represent a statistically significant difference at the 95% level according to Student's two sample t test. The values at the top right of each panel are the regional mean values of EC, NCP, and YRD, respectively.

6. "Climate + Emissions" represents the combined effect of both forcings. Have you tried linearly summing the individual effects of climate and emissions and comparing this sum to the combined effect? If not, this analysis should be performed and discussed.

Response:

Following the Reviewer's suggestion, we have added the following sentences in the last paragraph of Section 3.5:"Note that the sum of the individual effects of climate (Fig. 4a) and emissions (Fig. 4b) is not equal to the combined effects (Fig. 4c) due to the nonlinear relationship between the simulations (Dang et al., 2021).".

7. BVOC emissions are included in the "emissions" forcing. Since MEGAN is used, "climate" forcing also influences BVOCs. This raises the possibility of double-counting BVOC emissions in the combined effect. If double-counting is not an issue, please clarify this in the manuscript.

Response:

As shown in Section 2.2.2, BVOC emissions are computed using MEGAN, which is driven by meteorological conditions, and thus BVOC emissions are included in the "climate" forcing. The effects of emissions only include changes in anthropogenic emissions and biomass burning emissions, so we do not double-count BVOC emissions in the combined effects. To clarify this, we have added the following sentences in the second paragraph of Section 2.2.2: "Changes in all natural emissions are calculated by using projected climate change, which are considered as the effects of climate change.".

8. The manuscript states that meteorology explains 58–76% of the total change, yet net chemical production is described as the most important process. This appears contradictory. Please reconcile and clearly quantify the contributions of meteorological and chemical factors to the total change.

Response:

The effects of climate change are quantified by CfutEpd minus CpdEpd. This sentence here means that the key meteorological parameters selected among all climate variables can explain 58-76% of the total effects of climate change. For example, as shown in Table 4, in JJA, changes in SW, T2max, V850, RH, WS850, PBLH, and SLP explained 58% of the climate-induced changes in MDA8 O_3 over EC.

The climate-driven O_3 changes depend on the net effect of changes in physical and chemical processes, including net chemical production, PBL mixing, dry deposition, cloud convection, and horizontal and vertical advection transport. As shown in Section 3.3.2, net chemical production has a relative contribution of 34.0-62.5% among all the five processes, hence it is the most important process.

Therefore, as discussed above, they are not contradictory.

9. The manuscript omits some recent global studies on the climate effect on ozone, such as Bhattarai et al. (2024) (STOTEN; https://doi.org/10.1016/j.scitotenv.2023.167759). Discussing your findings in the context of these studies would strengthen the manuscript.

Response:

Following the Reviewer's suggestion, we have added the following sentences in the first paragraph of Section 3.2.2: "Our results are lower than the recent study by Bhattarai et al. (2024), who reported that climate change alone could lead to an increase of 5-15 ppbv in JJA MDA8 O_3 levels in EC over 2010-2050 under SSP1-2.6 scenario by using Community Earth System Model (CESM) and Community Atmospheric Model version 4 with chemistry (CAM4-chem).".

10. Figure 1: Clearly indicate what the difference plots represent in the caption and text. For example, is the change shown as CfutEfut − CpdEpd, or is it only the effect of climate? The figure caption should be self-explanatory.

Response:

Figure 1 shows projected climate change by GISS-E2.1 GCM from 2010 (averaged over 2005-2014) to 2045 (averaged over 2040-2049) under SSP1-1.9 scenario (see our response to your specific

Comment #2).

11. Line 409: There is no section called 5.1

Response:

We have changed "In Sect. 5.1" to "In Sect. 3.3.1".

12. Consider adding a discussion on the policy-relevant implications of the carbon neutrality scenario towards the end of the manuscript.

Response:

Following the Reviewer's suggestion, we have added discussions on the policy-relevant implications in the last paragraph of "Conclusion" section: "Additionally, MDA8 O_3 concentrations increase by changes in anthropogenic emissions in the future in DJF, MAM, and SON despite the large reductions in NO_x and VOCs (70-90%) in North China (Fig. S6) under SSP1-1.9 scenario, indicating an urgent need to find appropriate emission reduction ratios of VOCs and NO_x based on O_3 sensitivity to precursors and to climate for effective future O_3 pollution control in China.".

13. The carbon neutrality target is 2060, but you selected 2045 as the endpoint of your analysis. Is there any reason behind this?

Response:

The GCAP 2.0 meteorology only contains four time slices: pre-industrial era (1851-1860), recent past (2001-2014), near-future (2040-2049), and end-of-the-century (2090-2099). The closest time slice of GCAP 2.0 meteorology to carbon neutrality target year 2060 is 2040-2049. Therefore, the year 2045 (averaged over 2040-2049) is selected as the endpoint for the analysis considering the available GCAP 2.0 meteorology. To make this clear, we have added the following sentences in the first paragraph of Section 2.2.3: "The GCAP 2.0 meteorology are available for four time slices: pre-industrial era (1851-1860), recent past (2001-2014), near-future (2040-2049), and end-of-the-century (2090-2099).".

References:

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