Dear Owen Cooper,
we thank you very much for your detailed community comment of our manuscript egusphere-2024-324. Please find our replies to your comments below. Your original comments are repeated in italics, our replies in normal font, and text passages which we included in the text are in bold.

This paper provides a thorough analysis of the impact of transport emissions on present-day and future (2050) ozone based on three different SSPs. This is a complex endeavor requiring a wide range of tagged tracer runs and sensitivity tests, and it's not possible to consider every situation and account for every competing process (e.g. emissions, climate change, non-linearity).

Reply: Thanks a lot for your detailed comment and your overall positive feedback. We incorporated your suggestions, which helped to improve the revised manuscript strongly.

The authors are of course aware of this challenge and provide some extensive discussion in Section 7. I think this section would benefit from some further discussion regarding SSP3-7.0 and the expected impacts of climate change and increasing methane concentrations, as assessed in Chapter 6 of IPCC AR6 WG-I (Szopa et al., 2021).

Reply: Thanks for your suggestion. We changed the discussions section and especially included more information on methane and climate change aspects (see below for detailed comments).

Figure 6.4 in Szopa et al. shows an increase of the tropospheric ozone burden of roughly 10% from 2014 to 2050, based on SSP3-7.0, and much of this increase is due to projected increases in methane. Figure 6.20 in Szopa et al. indicated average ozone increases across South Asia of 8-10 ppb by 2050, under SSP3-7.0. These ozone increases seem to be much larger than your projected increases, as shown in your Figure 2. Part of this discrepancy could be due to differences in methane concentrations, as you discussed in Section 7.

Reply: Our model results for SSP3-7.0 show an increase over Southern Asia of 4–8 $\mathrm{nmol\,mol^{-1}}$. We agree that a very likely reason for this discrepancy is the methane effect (either because of fixed methane lower boundary conditions or differences in the methane life-time). We performed our methane sensitivity simulation only for the SSP2-4.5 projection in 2050. Here, we find an increase of ozone over Asia in the range of $1-2$ $\mathrm{nmol\,mol^{-1}}$ at ground-level due to the increased methane levels (see Figure 1).

We added the following note in Sect. 3.1:

However, the magnitude of the ozone change differs, especially our increase of ozone in SSP3.7-0 is lower as shown by Turnock et al.

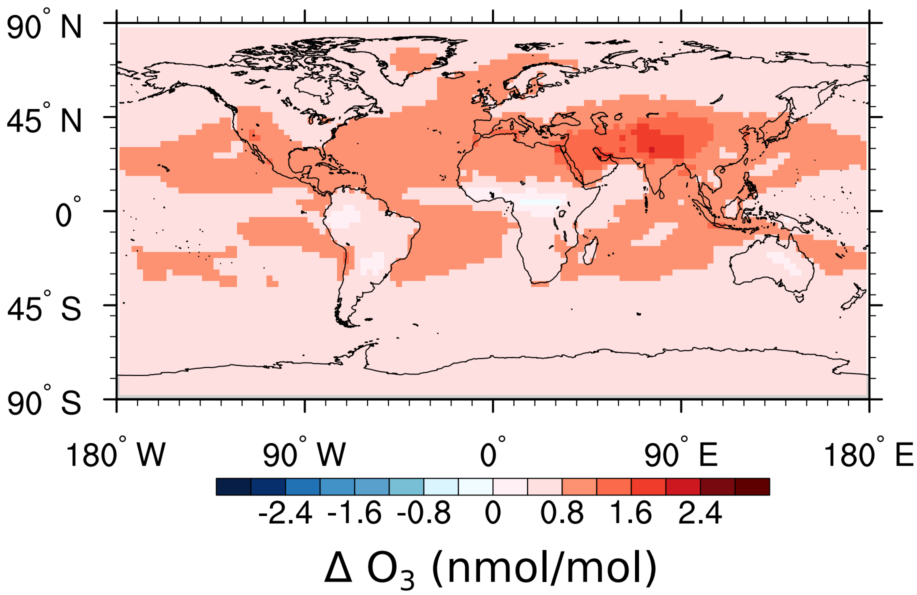

Figure 1: Absolute difference of ground-level ozone (in $\mathrm{nmol\,mol^{-1}}$) between SSP2-4.5 and the sensitivity simulation including increased methane lower boundary conditions.

(2020). Moreover, our results for the SSP3-7.0 does not show the strong decrease of ozone over the oceans as discussed by Zanis et al. (2022). Both differences can be expected, as we keep the methane lower boundary condition to present-day values, and because we do not include the effects of changing meteorology and climate and therefore also have constant water vapour concentrations in all simulations (see Sect. 7 for a detailed discussion).

But another likely explanation is the ozone climate penalty that impacts boundary layer ozone, as discussed by Zanis et al. 2022. Your paper does not mention the climate penalty and I think that it deserves some discussion. Another important finding of IPCC AR6 and Zanis et al. (2022) is that a warmer climate will be more humid, especially in the boundary layer, which will lead to a reduction of ozone lifetime in remote regions, such as over the oceans. .

Reply: Indeed, we need to address these points in more detail (see also comments from referee #3). The modified paragraph in the discussion reads:

Due to this approach, however, our model simulation do not consider changes in meteorology and climate between 2015 and 2050. Accordingly, emissions which are based on meteorological conditions (e.g. biogenic emissions, lightning-NO_x) are identical in all simulations. With climate change, these emissions are likely to increase (von Schneidemesser et al., 2015). This increase could alter the contributions of the anthropogenic emissions, for instance increased biogenic VOC emissions may affect the ozone production efficiency, while increased lightning-NO_x in the upper troposphere may compete with NO_x emissions from the aviation sector.

Moreover, increased biogenic emissions and changed atmospheric conditions (e.g. increased temperature and it's effects on kinetics) likely lead to an increase of ozone near highly polluted regions (knows as 'climate-penalty', Zanis et al., 2022). In addition, climate change likely leads to an decrease of ozone in remote regions due to the increase of water vapour (known as 'climate-benefit', Zanis et al., 2022). In addition, during periods of droughts and heat-waves, reduced ozone deposition to vegetation could increase ground-level ozone (Lin et al., 2020). Altogether, this could affect also the contributions of the traffic emissions. A reduced life-time of ozone, especially over the oceans, would likely lead to a reduction of ozone attributable to shipping emissions. Also long-range transport, especially the source-receptor relationships, might be affected by changes of the ozone lifetime. At the same time, the increase of ozone in polluted regions in a changing climate could affect ozone contributions especially from land transport emissions. Koffi et al. (2010) considered the effects of climate change on the ozone effects of transport emissions applying a 5 % emissions reduction (i.e. with the perturbation approach). Globally, they report a small decrease of the ozone changes caused by transport emissions due to climate change, but with strongly varying regional patterns. The effect of climate change on ozone contributions (i.e. applying a tagging approach) needs to be analysed in follow-up studies.

Your Figure 2 does not show a consistent reduction of ozone across the oceans under SSP3-7.0, probably because you use the same meteorology in 2015 and 2050; some discussion of this phenomenon would also be helpful.

Reply: We fully agree with your analysis. Due to the same meteorology in all simulations, water vapour is identical in all simulations; i.e. we only consider the change of ozone due the changes of the ozone precursor emissions (despite methane). We added a short note on this in the discussion of the figure. The changed text reads:

In most regions the decrease is in the range of $10-15$ nmol mol^{-1}, and exceeds 20 nmol mol^{-1} on the Arabian Peninsula. The overall changes of ground-level ozone for the three projections and regional features, such as the strong increase of ozone over Asia in SSP3-7.0, are in agreement with the analyses of CMIP6 simulation results by Turnock et al. (2020). **However, the magnitude of the ozone change differs, especially our increase of ozone in SSP3.7-0 is lower as shown by Turnock et al. (2020). Moreover, our results for the**

SSP3-7.0 does not show the strong decrease of ozone over the oceans as discussed by Zanis et al. (2022). Both differences can be expected, as we keep the methane lower boundary condition to present-day values, and because we do not include the effects of changing meteorology and climate and therefore also have constant water vapour concentrations in all simulations (see Sect. 7 for a detailed discussion).

Moreover, we added a further note during at the end of our discussion of the influence of the fixed methane levels:

Especially when considering our results of the SSP3-7.0 this effect should be kept in mind, because SSP3-7.0 shows even larger methane levels compared to SSP2-4.5. .

And a further note in the conclusion:

Especially for the results of SSP3 it should kept in mind that we apply present day methane-levels in all simulations. Applying the methane levels for SSP3 in 2050 likely leads to even larger ozone increases, but the responses of the different emission sectors on the methane increase are very complex and require further investigations in follow up studies.

Figure 5. Given that SSP1-1.9 has strongly decreasing transport emissions in all regions, I am surprised that none of the regional reductions produces ozone reductions in downwind regions. Why are there no ozone reductions in the receptor regions?

Reply: We are not sure whether we understand your comment correctly, or if this is simply a misunderstanding. The figure shows the absolute contribution of O_3^{tra}, which is always positive. So we don't expect to have negative values. However, if we plot the difference compared to PD (i.e. SSP1-1.9 minus PD) the values get negative showing that reductions exist (in agreement with Figs. 2 − 4, see also Fig. 2 in the reply which we also added to the revised supplement). Moreover, thanks to your comment we realized that the axis label for the color bar was wrong. We changed it from O_3 to O_3^{tra}.

Figure 7. If the future scenarios included climate change, with more humidity in the boundary layer and therefore a shorter ozone lifetime, would the ozone reductions due to shipping emissions reductions be even more pronounced?

Reply: This analysis seems plausible. We added a short discussion on this in the discussion Section. Yet, it remains to be tested whether counteracting effects on the tagged tracers exist. We added the following text:

If climate-change would be considered in addition, the ozone contribution from shipping emissions could be reduced even more strongly in

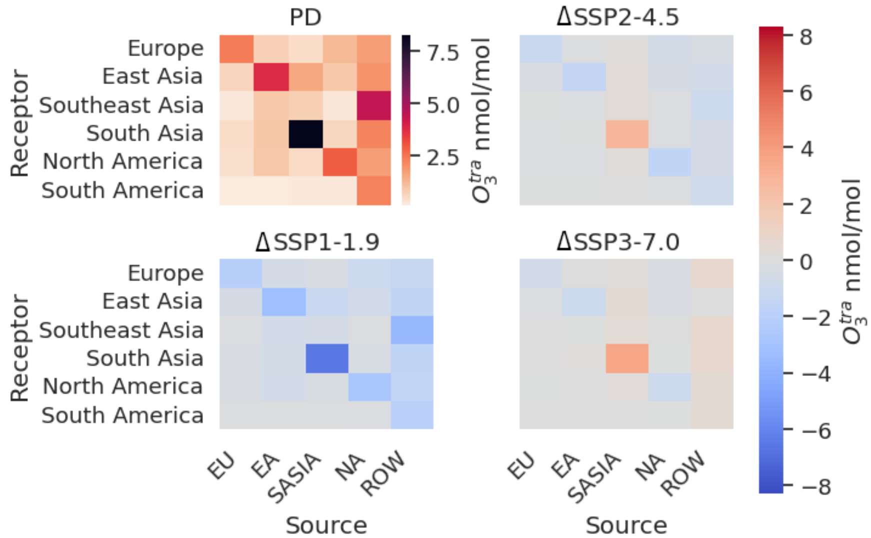

Figure 2: Source receptor analysis of the absolute contribution of land transport emissions to ground-level ozone (in nmol mol^{-1}). The values are mean values over 5 years and area weighted over the receptor regions. Exact definitions of the receptor regions are given in Sect. S9.1 in the Supplement. PD shows the absolute contributions for PD, all other panels show the difference of the absolute contributions compared to PD (e.g. SSP2-4.5 minus PD)

the future, given the likely reduction of ozone over the oceans due to increasing humidity (Zanis et al., 2022, see also disucssion in Sect. 7).

Section 4.4 A recent paper by Wang et al. (2022) indicates that the impact of aviation on the global tropospheric ozone burden is greater than suggested by previous studies. How does your analysis compare to that of Wang et al.?

Reply: This study was also mentioned by referee#1. It is difficult to compare our results directly to the results of Wang et al. (2022), because they calculate impacts on ozone levels from 1995 - 2017, while we calculate contributions at present day. However, as mentioned also in the reply to referee#1 our results in Fig. 10 and in Section 5.1. are in general agreement with Wang et al. (2022) and previous studies such as Dahlmann et al. (2011), indicating that aviation emissions are much more efficient in forming ozone compared to e.g. land transport emissions. Therefore, changes in aviation emissions can have stronger effects on tropospheric ozone compared to e.g. ground-level emissions. We added the study of Wang et al. (2022) accordingly in our manuscript.

Minor Comments: Figure S4. There is hardly any difference in surface ozone *between PD and SSP3-7, which is surprising. SSP3-7 is projected to have an increase in the tropospheric ozone burden, especially in the free troposphere. This should mean that ozone at high elevations sites (Greenland, the western USA, Tibetan Plateau, the Andes, Antarctica) should be higher under SSP3-7, but they appear to be almost the same. Is this due to your 2015 and 2050 simulations having the same methane concentrations, instead of higher methane in 2050?*

Reply: We double checked the figure and compared it with Fig. 2 in the manuscript. The figures are consistent, but we agree with your comment that the lack of increasing methane levels are likely to be one of the reasons. We added this point in the manuscript in the same part where we addressed the point with the missing decrease of ozone over the oceans (see your comment above). The changed text is:

However, the magnitude of the ozone change differs, especially our increase of ozone in SSP3.7-0 is lower as shown by Turnock et al. (2020). Moreover, our results for the SSP3-7.0 does not show the strong decrease of ozone over the oceans as discussed by Zanis et al. (2022). Both differences can be expected, as we keep the methane lower boundary condition to present-day values, and because we do not include the effects of changing meteorology and climate and therefore also have constant water vapour concentrations in all simulations (see Sect. 7 for a detailed discussion).

Line 622 When considering the impact of climate change on ozone, a relevant study is Lin et al. 2020, who show that drought and heat waves can limit ozone deposition to vegetation.

Reply: Thanks for the additional reference/point. This is added!

Line 410 When discussing ozone non-linearity, two relevant studies are Wu et al. (2009) and Wild et al. (2012). Similarly, when discussing differences in ozone production efficiency among regions, the study by Zhang et al. (2016) is very important as it demonstrated that ozone production efficiency is much greater in tropical regions than at northern mid-latitudes

Reply: Thanks for the additional reference. They are now included!

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