1 Answer to Reviewer 1

In this article, the authors explore representations of evapotranspiration in the chemistry-climate model EMAC, and how this impacts air temperature as well as air pollution, focusing mainly on tropospheric O3. *The remarks below need to be addressed before the manuscript can be accepted for publication.*

We are very grateful to Reviewer 1 for the thoughtful and constructive comments helping us improve the quality of the manuscript. We try to consider all the comments. Please find our reply (in blue) to your comments (black, italic) below.

This work presented is within the scope of the journal, and I think the results are robust and quite interesting. However, I have two major concerns:

1. I think the manuscript has a lot of build-up but then the implications on air quality are not discussed thoroughly. In other words, Section 3.5 needs to be expanded. I listed some suggestions below.

We agree with Reviewer 1. The section was extended, see comments below.

2. I had to re-read some text multiple times to understand what the authors wanted to say. I strongly recommend the re-writing of some parts. It would probably be a good idea to send the manuscript for proofreading.

We thank Reviewer 1 for pointing to this aspect. We will improve the general readability and clarity of the whole manuscript.

2 General comments:

While reading the manuscript I came across words written in US English and British English. Please be consistent.

We now stick to US English.

I think the manuscript would benefit from having an "Experimental design" section where you describe the experiment setup in detail. i.e., not just the relevant parameterisations, but also the submodules responsible for the land surface, vegetation, etc.

We add a 'Experimental design' section as section 2.1.4, which describes the set-up in more detail and use the respective lines from Section 2.1.1 (now 2.1):
'We perform dynamical simulations with 3-hourly instantaneous and average output for each plant-water stress parametrization at meso-scale (T106: 1.12 ° or $\approx$ 60km, middle atmosphere) for the period 2017/2018. The dynamical simulations apply a set of submodules (AEROPT, CLOUD, CLOUDOPT, CONVECT, GWAVE, MSBM, OROGW, ORBIT, QBO, RAD, SURFACE, TROPOP, VERTEX), similar to the set up used in Joeckel et al. (2016). The land–atmosphere exchange and vertical diffusion in EMAC is here described by the submodel VERTEX (Emmerichs et al., 2021). The key functionalities of VERTEX are explained in Section 2.1.2. The warm spell metric is calculated from a dynamical simulation at T42 (2.79 ° or $\approx$ 300km) covering 1979-2008. To assess the impact on air pollution (see Section 3.7) we conduct two chemistry simulations (T106, 2017/2018). These simulations employ additionally submodules describing emissions of atmospheric species (OFFEMIS, ONEMIS, BIOBURN, LNOX), gas exchange submodels (DDEP, AIRSEA). Chemical kinetics is calculated in the gas-phase by the submodule MECCA (Sander et al., 2019) and in cloud droplets by the submodule SCAV (Tost et al., 2006), JVAL (Sander et al., 2014). The chemical mechanism includes the basic gas-phase chemistry of ozone, methane, and odd nitrogen with in total 310 reactions and 155 species as in Joeckel et al (2016). Dry deposition of trace gases to vegetation is calculated according to the multiple resistance scheme which utilises the stomatal resistance calculated in VERTEX. The scheme is used here with six generalised land types. The vegetation canopy is represented as one system; i.e. the detailed structure and plant characteristics are neglected (one big-leaf approach). The leaves are horizontally oriented and the leaf density is

uniformly vertically distributed (Kerkweg et al., 2006; Emmerichs et al., 2021). Further information regarding the submodules can be found in Jöckel et al. (2010, 2016). Two additional chemistry simulations comprise the CO_2-doubling experiments. To reproduce the large-scale model dynamics, e.g. jet stream, the horizontal winds (divergence, vorticity) are nudged towards reanalysis data of ERA5 by Newtonian relaxation with an e-folding time of 6-24 hours for all wavenumber truncations in the spectral space similarly to van Garderen et al. (2021). Temperature and pressure are not nudged. This selective nudging is applied for conducting storyline simulations (Shepherd et al., 2018). This allows the model thermodynamics to respond freely to the process modifications implemented in this study.'

It is not clear what vegetation representation is being used. It was only later in L357/358 that I realised that you have no vegetation in your model. This should be made more clear. The suggestion above would help to clarify this.

At the end of Section 2.1.2, we added the sentence 'EMAC contains no dynamic vegetation model. Vegetation is represented as a "big leaf" affecting exchanges of water, energy and trace gases depending on leaf area index, soil moisture and other parameters. This is described in detail in Section 2.1.3.'

Figure captions are way too short. Generally, one should be able to understand the figure completely from the caption without referring to the main text (i.e. self-describing). E.g., Fig. 2 - "Annual mean maximum assimilation" Assimilation of what?

There, CO_2 assimilation is meant. We extend this caption with this information.

Fig. 3 was not discussed enough in the text. Please update the figure's caption (see above), and also provide the geographical extent of the areas considered.

We discuss Fig.3 verbosely in line 253-267 including the differences and features of the regional plots. The text is rewritten with shorter sentences and more clear structure to the following:
'Only a minor different change of the plant-water stress and subsequent variables among each other is seen in the regional plots (Fig. 3). Thus, the the linear fraction and the exponential formulation can be interpreted similarly. All three stress functions based on leaf water potential (*LWPfrac*, *LWPexp*, *CLM5*) introduce an additional dependence of the modelled transpiration on air temperature (except in the arid climate). On the one hand, this dampens the increase of transpiration with rising temperature. Accordingly, the amplitude of the diurnal cycles decreases (Figure 3). On the other hand, the diurnal cycle of plant-water stress show firstly variations with temperature during day which is an observed phenomena according to Xiao et al. (2021). In contrast to *LWPfrac* and *CLM5* which predict not only the same ψ but also the same $f(\psi)$, *LWPexp* estimates a higher (negative) ψ in most regions (shown in Figure 3). This can be explained via the temperature-transpiration feedback expected in dry climates (ARP and African savanna). In contrast to *LWPfrac* and *CLM5*, the simple exponential function in *LWPexp* yields a stress factor close to zero unrealistically shutting down the mesophyll conductance and the photosynthetic activity. The analysis of *noWP* and *DEFmulti* simulations shows only small local changes in transpiration (within the monthly range of variance) which impacts the annual estimate only by $\pm$10-15 %. This is because neglecting the wilting point decreases the plant-water stress (f_{W_s}) by only 10 % in all dry vegetated regions (dry climate: $W_s < 0.35 * F_c$, see Seneviratne et al. (2010)) and thus transpiration is only marginally affected.'
The caption of Figure 3 is extended, and regional definitions are added.

I find some of your colour bars confusing. When using a diverging color bar, please decide whether you want the min/max to be pointy or not, but be consistent! The min/max of the colour bars is misused in most of the figures presented.

We agree with Reviewer 1. All diverging color bars were adapted

Fig. 4 - Fix the colour bar for subplot (a). Caption - Which panels are from EMAC and which are not?

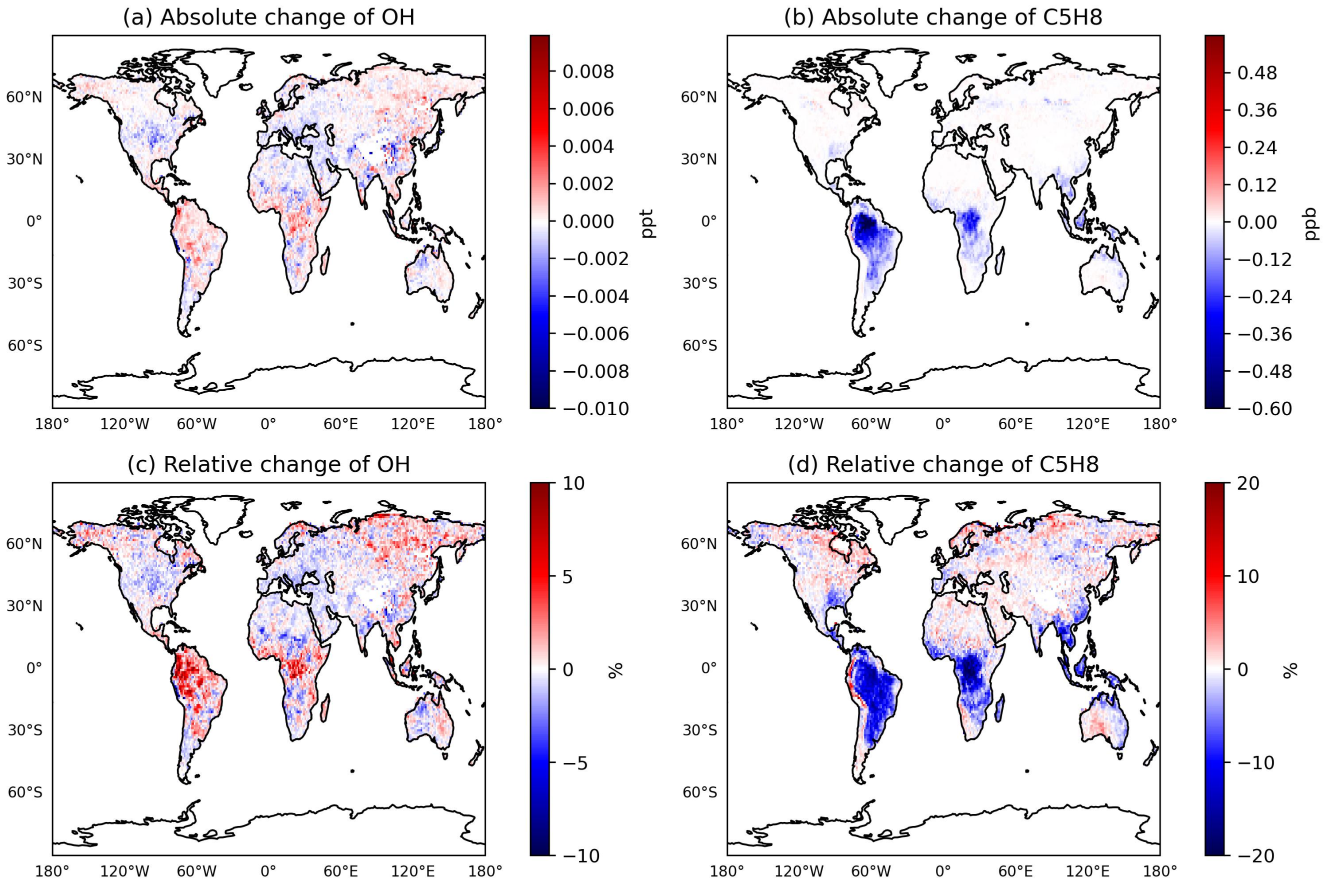

Figure 1. Annual mean relative change (*LWPfrac-REF*) of OH (a) and isoprene (b) mixing ratio at the surface (for regions with isoprene>50 ppt).

Panel b-d are from EMAC, this information was added in the caption

Fig. 8 - Color bars. Why do you have a change in stomatal conductance over deserted regions, e.g., the Sahara desert? Please explain this, and if the values are negligible consider applying a mask.

Until the up-scaling of stomatal conductance to the canopy level (see ECMWF (2021), eq. 8.123) the intermediate calculations, are at leaf level. Thus, we apply also here a mask now to neglect non-vegetated areas like the Sahara desert.

Section 3.5: In the supplement, you show a strong decrease in isoprene mixing ratios. Could you also show the absolute difference not just the relative (%) change?

Yes, we added the absolute difference for isoprene mixing ratio.

From Fig. 6 I would expect a strong increase in isoprene emissions given the increase in surface temperatures. Would be nice to dig in deeper here and quantify the increase in surface isoprene emissions and see how this increase compares to the

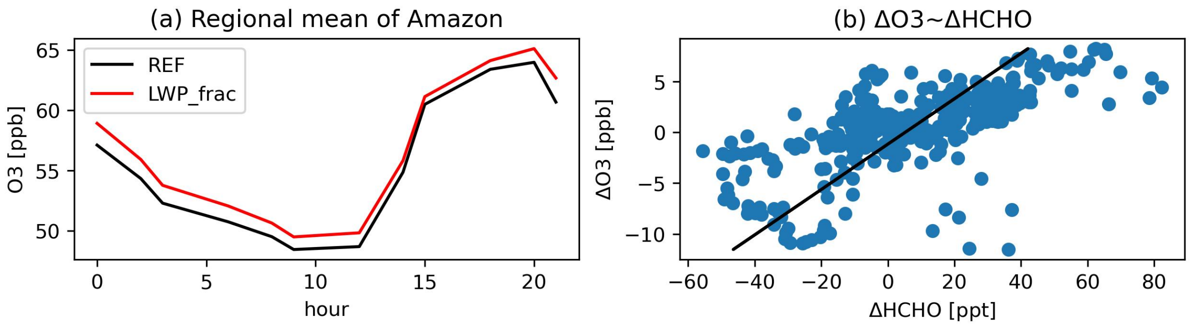

Figure 2. (a) Regional mean diurnal cycle of O3 in the Amazon (Monsoon region, definition in Fig. 3) and (b) linear regression of the absolute difference (*LWPfrac-REF*] formaldehyde (HCHO) with O3 surface levels at the ATTO (Amazon Tall Tower Observatory) site in November 2018 (dry season).

decrease in isoprene concentrations from enhanced OH oxidation. Also, provide details on the isoprene emissions and sensitivities. Are you using MEGAN?

We add further details to the text:
'The plant emission activity, as modelled by the MEGAN model (Model of Emissions of Gases and Aerosols from Nature) increase with higher temperature up to a value of approximately 40° C (Guenther et al., 2006). The increasing emissions lead to a linear increase of O3. As shown in Figure 2a and b for the Amazon, the O3 increase by 0.34 ppb per 1 ppb increase in formaldehyde (HCHO). HCHO is a direct product of isoprene oxidation with a lifetime of a few hours and thus often used as a proxy for isoprene emissions (Palmer et al., 2003). In the outer tropics, O3 additionally increase with rising soil emissions of nitrogen oxides (NO), which is an important O3 precursor source in remote regions (far from anthropogenic emissions).'

Fig. S1: In some places over Africa (e.g. 20-30 deg S), you show a decrease in the OH radicals but this does not correspond to an increase in isoprene. Why is that? This seems to violate your hypothesis that isoprene concentrations go lower because of increased loss by OH. Similarly, could you explain the hotspot (increase in isoprene) over Antarctica where there are no apparent corresponding changes in OH?

Thank you for mentioning this interesting features. These African places experience significant NO soil emissions. The higher NOx emissions limit the oxidation of plant emissions (compared to other remote regions) (Monks et al., 2015). Isoprene on Antarctica stems from transported emissions over the ocean but this can be treated as insignificant. Thus, we here show only changes where the surface isoprene level exceeds 50 ppt.

Please include some limitations in your study. E.g. No vegetation representation, and the fact that the biosphere and BVOC emissions do not respond to changes in tropospheric chemistry e.g. ozone concentrations.

The model represents vegetation and related coupling processes. We made clear in the model description that it, however, has no dynamical vegetation model and the LAI as only information. The plant damage by O3, which is probably meant here with the second aspect, is out of the scope of this study and will be published soon in a separate study. The limitations are considered here at the end of Sect. 3.5 as follows:
'The here discussed changes do not include the O3 damage to plants, i.e the biosphere-atmosphere exchange. However, from experiments like by Sadiq et al. (2017) we can learn that an implementation of this response amplifies the O3-vegetation feedback. Since the caused O3-increase limits the plant activity reducing transpiration and dry deposition further which in

turn enhances the O3 levels. No clear feedback was found for isoprene emissions while the reduced ecosystem production contributes only minor to the overall feedback.'

3 Minor comments:

L26: When writing "e.g." for citations, it is generally expected that you mention more than one study. Please correct all other instances in the manuscript. we added references in these places or re-formulated to be more concrete

L29: "(plant's pores)" - I don't think this is needed here. removed

L36/37: "Currently" should go at the start of the sentence. changed

L51: "non-stomatal processes in plants" - like what? like mesophyll diffusion and biochemical limitations, added to the text

L61: "GLEAM" - Is this an acronym? Please define acronyms on their first instance. defined already in the Section 2.2.2

L61: More details are needed on the EUMETSAT satellite you are referring to. The details are described in Section 2.2.1

L90: Include unit for LAI m2/m2. included

L98: Latter not "later" changed

164: EUMETSAT was already used. Please define in the first instance. It is defined in the description of EUMETSAT

L184/85: Not clear what you mean here. Do you mean the sum of the bare soil, short/tall vegetation evapotranspiration per grid box? yes exactly

L193: mmday-1 - why italic? we write now written units in the text consistently in italic font.

L246/253: Text not clear. Please consider rewriting this part. "Saharian" - do you mean Sahara desert? yes, is corrected.

L250: The distribution of transpiration inf Fig. 2b follows patterns of vegetation distribution e.g. LAI. Why would the additional soil moisture in the tropics explain the geographical distribution? The atmospheric moisture deficit not the soil moisture is meant

L302: "African desert" - Sahara desert changed

L308: "...in the southern part of South America ....." different wording

L344: "to to" corrected

L352: "... respective changes in tropospheric ozone...." rephrased to 'shows the impacts of using the *LWPfrac* plant-water stress on troposheric ozone'

L392/393: Provide more details on the "bucket model" in EMAC or JSBACH. The bucket model is already described in Sect. 2.1.2

L394: JSBACH define the model acronym. defined now

L405: "...(LSMs) generally agree with..." The line was adapted

*L414: Double brackets.*changed

L401/402: Give more details on the 'ozone-climate penalty'. What is the benefit suggested in Zanis et al. 2022? We added the sentence:

'However, a recent multi-model projection suggests a climate benefit on a global average, i.e. a decrease of ozone as consequence of global warming.'

References

ECMWF: IFS Documentation CY47R3, IFS Documentation, ECMWF, 2021.

Emmerichs, T., Kerkweg, A., Ouwersloot, H., Fares, S., Mammarella, I., and Taraborrelli, D.: A revised dry deposition scheme for land–atmosphere exchange of trace gases in ECHAM/MESSy v2.54, Geoscientific Model Development, 14, 495–519, https://doi.org/10.5194/gmd-14-495-2021, publisher: Copernicus GmbH, 2021.

Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P. I., and Geron, C.: Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature), Atmospheric Chemistry and Physics, 6, 3181–3210, https://doi.org/10.5194/acp-6-3181-2006, 2006.

Jöckel, P., Kerkweg, A., Pozzer, A., Sander, R., Tost, H., Riede, H., Baumgaertner, A., Gromov, S., and Kern, B.: Development cycle 2 of the Modular Earth Submodel System (MESSy2), Geoscientific Model Development, 3, 717–752, https://doi.org/10.5194/gmd-3-717-2010, publisher: Copernicus GmbH, 2010.

Jöckel, P., Tost, H., Pozzer, A., Kunze, M., Kirner, O., Brenninkmeijer, C. A. M., Brinkop, S., Cai, D. S., Dyroff, C., Eckstein, J., Frank, F., Garny, H., Gottschaldt, K.-D., Graf, P., Grewe, V., Kerkweg, A., Kern, B., Matthes, S., Mertens, M., Meul, S., Neumaier, M., Nützel, M., Oberländer-Hayn, S., Ruhnke, R., Runde, T., Sander, R., Scharffe, D., and Zahn, A.: Earth System Chemistry integrated Modelling (ESCiMo) with the Modular Earth Submodel System (MESSy) version 2.51, Geoscientific Model Development, 9, 1153–1200, https://doi.org/10.5194/gmd-9-1153-2016, publisher: Copernicus GmbH, 2016.

Kerkweg, A., Buchholz, J., Ganzeveld, L., Pozzer, A., Tost, H., and Jöckel, P.: An implementation of the dry removal processes DRY DEPosition and SEDImentation in the Modular Earth Submodel System (MESSy), Atmospheric Chemistry and Physics, 6, 4617–4632, https://doi.org/10.5194/acp-6-4617-2006, publisher: Copernicus GmbH, 2006.

Monks, P. S., Archibald, A. T., Colette, A., Cooper, O., Coyle, M., Derwent, R., Fowler, D., Granier, C., Law, K. S., Mills, G. E., Stevenson, D. S., Tarasova, O., Thouret, V., von Schneidemesser, E., Sommariva, R., Wild, O., and Williams, M. L.: Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer, Atmospheric Chemistry and Physics, 15, 8889–8973, https://doi.org/10.5194/acp-15-8889-2015, 2015.

Palmer, P. I., Jacob, D. J., Fiore, A. M., Martin, R. V., Chance, K., and Kurosu, T. P.: Mapping isoprene emissions over North America using formaldehyde column observations from space, Journal of Geophysical Research: Atmospheres, 108, https://doi.org/https://doi.org/10.1029/2002JD002153, 2003.

Sadiq, M., Tai, A. P. K., Lombardozzi, D., and Val Martin, M.: Effects of ozone–vegetation coupling on surface ozone air quality via biogeochemical and meteorological feedbacks, Atmospheric Chemistry and Physics, 17, 3055–3066, https://doi.org/10.5194/acp-17-3055-2017, 2017.

Sander, R., Jöckel, P., Kirner, O., Kunert, A. T., Landgraf, J., and Pozzer, A.: The photolysis module JVAL-14, compatible with the MESSy standard, and the JVal PreProcessor (JVPP), Geoscientific Model Development, 7, 2653–2662, https://doi.org/10.5194/gmd-7-2653-2014, 2014.

Sander, R., Baumgaertner, A., Cabrera-Perez, D., Frank, F., Gromov, S., Grooß, J.-U., Harder, H., Huijnen, V., Jöckel, P., Karydis, V. A., et al.: The community atmospheric chemistry box model CAABA/MECCA-4.0, Geoscientific model development, 12, 1365–1385, https://doi.org/10.5194/gmd-12-1365-2019, 2019.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J.: Investigating soil moisture–climate interactions in a changing climate: A review, Earth-Science Reviews, 99, 125–161, https://doi.org/10.1016/j.earscirev.2010.02.004, 2010.

Shepherd, T. G., Boyd, E., Calel, R. A., Chapman, S. C., Dessai, S., Dima-West, I. M., Fowler, H. J., James, R., Maraun, D., Martius, O., et al.: Storylines: an alternative approach to representing uncertainty in physical aspects of climate change, Climatic change, 151, 555–571, https://doi.org/https://doi.org/10.1007/s10584-018-2317-9, 2018.

Tost, H., Jöckel, P., Kerkweg, A., Sander, R., and Lelieveld, J.: Technical note: A new comprehensive SCAVenging submodel for global atmospheric chemistry modelling, Atmospheric Chemistry and Physics, 6, 565–574, https://doi.org/10.5194/acp-6-565-2006, 2006.

van Garderen, L., Feser, F., and Shepherd, T. G.: A methodology for attributing the role of climate change in extreme events: a global spectrally nudged storyline, Natural Hazards and Earth System Sciences, 21, 171–186, https://doi.org/10.5194/nhess-21-171-2021, publisher: Copernicus GmbH, 2021.

Xiao, J., Fisher, J. B., Hashimoto, H., Ichii, K., and Parazoo, N. C.: Emerging satellite observations for diurnal cycling of ecosystem processes, Nature Plants, 7, 877–887, https://doi.org/10.1038/s41477-021-00952-8, number: 7 Publisher: Nature Publishing Group, 2021.