Authors' response to reviewers' comments on "Simulated seasonal impact on middle atmospheric ozone from high-energy electron precipitation related to pulsating aurorae" by Verronen et al.

Please find below our answers (in blue) to the comments (in black).

Response to the comments of Referee #1

General Comments: The article "Simulated seasonal impact on middle atmospheric ozone from high-energy electron precipitation related to pulsating aurorae" by Verronen et al. presents the results of model simulation on the impacts of the energetic electron precipitation related to pulsating aurorae (PsA-EEP) to the middle atmospheric ozone. However, there are several issues need to be addressed before the consideration of the publication.

Response to general comments: We would like to thank the reviewer for the comments and appreciate the time devoted to the evaluation of our paper.

1. Regarding "There is also an open question of the relative contribution of PsA-related energetic electron precipitation (PsA-EEP) to the total atmospheric forcing by solar energetic particle precipitation (EPP)" in the abstract, why did you choose the pulsating aurora over the ordinary diffuse or discrete aurorae to investigate the EPP impact on ozone chemistry in the polar mesosphere? What makes the pulsating aurora special over the ordinary aurorae, in particular, with regard to their atmospheric impacts? How are PsAs distinguished from the ordinary diffuse aurora or discrete aurora in terms of energy, occurrence rate and duration, latitudinal extent etc. to affect the atmospheric chemistry and possibly dynamics? It is critical to justify the results of the study especially when the simulation impacts of PsA-EEP seem to be similar to typical EPP impacts.

Response: Electron precipitation related to pulsating aurorae (PsA-EEP) has recently received increasing research attention because of its different characteristics compared to other types of aurorae. Specifically, PsA-EEP extends to higher electron energies than any other morphological type of auroral precipitation and thus leads to direct ozone depletion in the mesosphere through HO_x and mesospheric production of NO_x (Turunen et al., 2016, Miyoshi et al., Penetration of MeV electrons into the mesosphere accompanying pulsating aurorae, Sci. Rep., 11, 13724, https://doi.org/10.1038/s41598-021-92611-3, 2021). Further, PsA-EEP has a higher occurrence rate and longer duration (Bland et al., 2019), and greater latitudinal extent than other auroral precipitation (Bland et al., 2021). All these PsA-EEP features contribute towards stronger atmospheric impacts, and justify our focus on PsA-EEP here.

In the revised manuscript (Section 1), we discuss these special PsA characteristics and atmospheric implications.

2. How was the PsA-EEP taken into account within the model as an energy inputs during the simulation period of 18 months in comparison with other EPP energy inputs? Please describe it specifically. In Section 2, the PsA-EEP ionization rates applied in the study were described such as its application of every other night at the local time hours of 00 MLT to 06 MLT, homogeneously between 60 and 72 deg geomagnetic latitude. I am wondering how this application of PsA-EEP forcing is realistic and how different it is from regular diffuse and discrete auroral forcing. Authors mentioned that all simulations included the background EPP forcing used in WACCM, i.e. solar protons, auroral electrons, and galactic cosmic rays. How the applied PsA-EEP forcing is distinguished from these background EPP forcing? This seems to be critical to explain the difference between the full-PsA and no-PsA simulations in Figure 2, assuming that the no-PsA simulation includes all the background EPP forcing.

Response: We argue that the characteristics of our PsA-EEP forcing are realistic. The occurrence rate, latitude extent, and MLT distributions are based on most recent research on PsA and well justified. Nevertheless, simplifications have been made to create a usable forcing data set for the simulations. Particularly, the well-known rapid pulsating patterns (patchiness) are not taken into account, as their implementation in the model would be challenging without detailed knowledge of their statistical characteristics. Determination of these characteristics would require a separate, extensive effort (e.g., an artificial intelligence application on large amounts of PsA data). However, the simplifications we made are justified by the aim of assessing the potential impact of PsA-related EEP toward its upper limit. It should be noted that similar simplifications of latitudinal extent and temporal variability are typical in simulations for other types of EEP as well.

The background auroral forcing used in our simulations is provided by a statistical model driven by the geomagnetic Kp index. The Kp-aurora is described by, e.g., Smith-Johnsen et al., JGR Space, 123, 5232–5245, doi:10.1029/2018JA025418, 2018, and references therein. In the current setup, it provides daily average ionization rates around geomagnetic latitudes 65°–70° (auroral oval). The Kp-aurora has a characteristic energy of 2 keV and a Maxwellian distribution and it is restricted to altitudes above 90 km ($E < 30$ keV), i.e. it has no direct ionization impact in the mesosphere. With the applied PsA-EEP energy range of 10–1000 keV, PsA-EEP provides a major extension of EEP into mesospheric altitudes. Compared to the Kp-aurora, there is also an increase in latitudinal extent by a few degrees, and a stronger diurnal variability from the MLT dependency.

The background GCR ionization rates are the daily average values recommended for the Coupled Model Intercomparison Project (Matthes et al. 2017). GCR affects all latitudes and is stronger in the polar regions. However, the GCR ionization peaks in the lower stratosphere and day-to-day variability is small. Compared to PsA, it provides very low, nearly-static background ionization in the mesosphere and above.

The background solar proton ionization rates are the daily average values recommended for the CMIP6 project (Matthes et al. 2017). In our simulations, proton ionization affects latitudes above 60°, geomagnetic, and altitudes below about 90 km. Proton background is small at most times, but can completely dominate the mesospheric and upper stratospheric ionization during major events. During our simulation period, however, there were no large solar proton events and thus proton ionization remained low compared to the PsA-EEP ionization (ftp://ftp.swpc.noaa.gov/pub/indices/SPE.txt, NOAA, accessed in May, 2021). We note that it is important for our study to include the background GCR, SPE, and aurora, so that PsA-EEP additional impact can be assessed realistically. For this purpose, the background EEP that we have applied is well-suited.

In the revised manuscript, Section 2, we have added a paragraph that discusses the background EPP input and how the PsA-EEP adds to it, in order to clarify the difference between the full-PsA and no-PsA simulations.

3. At the end of Section 1, authors raised a few questions as “The question that remains whether PsA is common enough to cause an appreciable longer-term effects over a wider range of latitudes and local times, and whether these could be detected by satellite-based observations. Furthermore, an outstanding issue in simulations is the shortcomings in EPP-related enhancement of wintertime odd nitrogen. In this context, understanding the PsA-EEP-driven odd nitrogen production could be particularly useful because PsA events are most common in wintertime. Finally, the PsA-EEP high-energy end can directly increase the mesospheric NO_x production which should enhance the indirect ozone impact in the upper stratosphere.” Are these questions answered by this study? What are the fundamental differences of the current study from previous studies?

Response: Yes, we show that PsA-EEP can potentially have appreciable longer-term atmospheric impacts, and that part of the NO_x-shortage found in previous simulation work could be covered by considering PsA-EEP. The novelty to the previous PsA-EEP studies is that we consider long-term impacts using a global chemistry-climate model, thus the impact of atmospheric dynamics on the NO_x/ozone response is included e.g. through the NO_x transport.

We have revised the end of Section 1 and Conclusions to clarify these points.

4. Regarding thermo-PsA simulation, it was mentioned to separate the impacts from thermospheric and mesospheric forcing. However, it seems very unrealistic and artificial to me. Can it be regarded as the pulsating aurora with relatively low-energy electrons? If so, why didn't you set two different PsA EPPs with high and low energy, instead of artificially setting the zero-ionization below 85 km? This way should be more physically consistent within the model.

Response: In the thermo-PsA simulation, we set the PsA-EEP ionization below 85 km to zero. A similar forcing scenario could be achieved by setting the electron flux to zero at energies larger than about 40 keV. However, that approach would also remove the along-path thermospheric ionization due to >40 keV electrons. Because our aim is to separate the response to direct thermospheric and mesospheric forcing, our approach does this without losing the high-energy electron impact in the thermosphere (i.e. the thermospheric ionization in full-PsA and no-PsA simulations is the same). While our approach is somewhat artificial, it, however, provides us a useful way to assess the importance of direct mesospheric ionization.

In the revised manuscript (Section 2), we discuss this and justify our approach better.

5. Regarding the solar activity effects in the study, authors mentioned as "Note that the simulation period is in the ascending phase of the solar cycle right after a record minimum in solar activity, thus the background EPP forcing was relatively low, making it easier to identify the PsA-EEP impact." Does it mean that the occurrence of PsA is not affected by solar activity while the background EPP forcing is weak during low solar activity? Is PsA different from background EPP in terms of solar activity dependence?

Response: We mean that the selected time period had a low solar activity, so that the background EPP, e.g. Kp-Aurora, was relatively low compared to what they would be closer to solar maximum. Thus if the same PsA-EEP forcing was applied during solar maximum, we would expect to have relatively smaller response compared to the background EPP. However, the selection of a solar minimum time is inline with our approach of finding the upper range of the PsA-related impact. While PsA does not require strong or extreme solar wind driving (Tesema et al., 2020), which means that PsA reduces less than other aurorae during solar minima, it still varies with solar activity similar to other types of aurora.

In the revised manuscript, we clarify this issue in Section 2.