Dear Reviewer, thank you very much for your positive and constructive comments. Please find our responses to your comments below, highlighted in green.

Review of the paper

Implementation of solar UV and energetic particle precipitation within the LINOZ scheme in ICON-ART by Maryam Ramezani Ziarani, Miriam Sinnhuber, Thomas Reddmann, Bernd Funke, Stefan Bender, and Michael Prather

The paper documents the implementation of an upper boundary condition for NOy (UBC-NOy), and a linearized ozone parametrization (LINOZ) into the ICON-ART model. The LINOZ parametrization is further extended by terms describing ozone depletion by enhanced NOy mixing rations. The UBC-NOy allows to account for NOy enhancements during periods of high energetic particle precipitation (EPP). Besides this, the spectral solar irradiance (SSI) variability with the 11-year solar cycle is considered, by providing LINOZ coefficient tables for solar maximum and solar minimum conditions which can be scaled with the F10.7 cm solar ux. The advantage of this modelling approach is its efficiency.

General comments

The paper describes a very efficient way to incorporate transient, time-dependent ozone to be used in long climate projection simulations with variable SSI and EPP forcing. After some minor changes, and some additional discussions, I recommend the publication in GMD.

The introduction lacks a discussion of alternative, existing options for e effectively simulating transient ozone, such as the parameterization of Cariolle and Teyssedre (2007), or SWIFT (Wohltmann et al., 2017; Kreyling et al., 2018)

The following paragraph is added to the introduction: "Several parameterizations have been developed for simulating transient ozone in chemistry-climate models. The scheme introduced by Cariolle and Teyssèdre (2007) provides a linear parameterization of ozone photochemistry, including a representation of polar ozone loss, which we also adopt in our setup. Another example is the SWIFT scheme (Wohltmann et al., 2017; Kreyling et al., 2018), which uses an efficient approach based on a fourth-order polynomial fit to full chemistry simulations. While SWIFT offers high accuracy and speed, it was originally designed for use with Lagrangian transport models, making it less directly applicable to our ICON setup. In this study, we use the LINOZ scheme, which provides a computationally efficient and dynamically consistent alternative, suitable for integration into global models that requires interactive yet fast ozone chemistry."

The authors should discuss the possibility of using the model system for greenhouse gas scenarios. Is it possible to simulate realistic ozone concentrations with elevated GHGs using ICON-LINOZ?

The following paragraph is added to the introduction: "The ICON-LINOZ is capable of simulating ozone under changing greenhouse gas (GHG) conditions. N2O and CH4 are calculated from prescribed surface flux boundary conditions, allowing their long-term evolution to influence stratospheric ozone through interactive chemistry (Hsu and Prather, 2010). Therefore, the model can reflect the impact of elevated GHGs on ozone concentrations. If future scenarios consist of substantial shifts in these trace gases or in the background climate state, the LINOZ tables can be regenerated around a new reference state to maintain accuracy in the ozone response. This flexibility makes ICON-LINOZ suitable for studies of ozone-climate interactions under a range of future GHG pathways."

The possibility of extreme scenarios, such as the CMIP 4xCO2 scenario, which was also discussed by Meraner et al. (2020) in connection with the parameterization of Cariolle, should also be discussed. Does the LINOZ parameterization work for such extreme CO2 scenarios?

The following paragraph is added to the introduction: "The LINOZ parameterization has been shown to perform well under extreme climate scenarios, such as the CMIP 4× CO_2 case discussed by Meraner et al. (2020). In their study, both the Cariolle and LINOZ v1 schemes produced reasonable ozone responses to substantial temperature increases. Our implementation of LINOZ v3 (Hsu and Prather, 2010) builds on this by addressing a key limitation identified in Meraner et al. (2020) which is the absence of Quasi-Biennial Oscillation-related feedback on NOy due to vertical transport in LINOZ v1. In LINOZ v3, this coupling is included, allowing for more realistic simulation of ozone and NOy variability, particularly in the tropical stratosphere above 10 hPa. This confirms that the ICON-LINOZ system remain applicable and robust for studying ozone under high-CO_2 scenarios."

Specific comments

Line 91: ...by a joint development between the German Weather Service (DWD) and ... Actually ICON is developed by the ICON partnership. Please replace with: . . .by a joint development between the German Weather Service (DWD), the Max Planck Institute for Meteorology (MPI-M), Deutsches Klimarechenzentrum (DKRZ), the Karlsruhe Institute of Technology (KIT), and the Center for Climate Systems Modeling (C2SM) …

Revised.

Line 95: ICON has terrain following height levels only on the lower levels. They turn into levels at constant height levels.

Revised to: It uses a hybrid vertical coordinate system that is terrain-following near the surface and transitions to constant height levels in the upper levels.

Line 97: Which physics parametrizations are used? Later you refer to the ICON(NWP) physics package. This information should be given here already.

This sentence is added: "Our study relies on ICON(NWP) physics package."

Lines 124-125: The differential equation needs more explanations. Which variables in the equation represent the tabulated coefficients? How many coefficients are included?

Requested information are added.
"The tabulated coefficients used in the model include: the reference tendency term (P − L)_i^0, and the first-order partial derivatives with respect to each variable: ∂(P − L)_i/∂f_j, ∂(P − L)_i/∂T, and ∂(P − L)_i/∂co_3. These coefficients have been calculated for 25 pressure levels, 18 latitudes, and 12 months (Hsu and Prather, 2010)."

Lines 137-138: ...applied three model levels below the upper boundary. ...
Reformulate: . . .applied to the three uppermost model levels. …

Revised.

Line 166: You mention an upper atmosphere setup extending to 150 km. Is the model development described in this paper also tested and available for this upper atmosphere extension of ICON? If not, you should not mention the upper atmosphere extension here, as it is confusing.

True, It is removed.

Lines 195-196: ...where the UBC is applied three model levels below the top to avoid noise from the sponge layer. ... Please be more specific. Is the UBC applied at the three uppermost model levels, or at three levels starting at three levels below the model top? This is related to the comment to Lines 137-138.

UBC applied at the three uppermost model levels. It is revised to avoid confusion.

Line 199: You describe the method to prescribe NOy volume mixing ration (VMR), here. This should already be introduced in Section 2.3 (Lines starting at 137).

The paragraph is moved as suggested.

Lines 220-224: Some details about the use of variable SSI are missing. For example, the number of bands used in the photochemical box model. A somewhat more detailed description of the method of Hsu and Prather (2010) Hsu and Prather (2010) is also missing, instead of referring to the reference.

The preparation of the SSI data is better described by the term integration rather than the term interpolation.

The paragraph is revised: "In addition to particle forcing, we included solar UV variability into ICON-ART to account for induced ozone changes, primarily in the tropical stratosphere. The photochemical box model calculating the LINOZ tables applies a solar spectrum provided in 77 spectral bins. In order to implement solar spectral variations, the LINOZ tables must be re-calculated using solar spectra representing solar maximum and solar minimum conditions. The spectra applied are based on two spectra taken during the ATLAS missions in Nov 1989 (solar maximum) and 1994 (solar minimum) and prepared as described in Kunze et al. (2020) to comply with recent measurements of the solar constant. After transferring the spectra to the 77 spectral bins of the photochemical box model (Prather 1990), McLinden et al. 2000) (here version 8.0) we calculated two sets of tables and used them for solar maximum and solar minimum runs.”

Line 275: You write: ...linked to an Enhanced Stratospheric (ES) event ... Probably you meant Elevated Stratopause (ES) events.

Revised.

Figure 8: Please adapt the contour level interval (0.3, or 0.5 %) of the shading, to better match the range of the data.

Revised.

Technical corrections

Line 103: Tras ... replace with: Trace …

Revised.

Line 107: ...in which a tracer has a fixed lifetime for depletion, is considered ... reformulate: . . .considering a tracer with a fixed lifetime for depletion …

Revised.

Line 109:- And, full ... replace with:- and a full ...

Revised.

Line 153: ...Linoz ... Please use consistently in the paper: . . .LINOZ …

Revised.

Line 174: Three model experiment ... Add an s ...experiments …

Revised.

Line 189: please change ...derived from both simplified parametrization scheme ... to ...derived from both, a simplified parametrization scheme …

Revised.

Figure 1: You should add labels for the experiments on top of each column.

Revised.

Lines 226-227: change ...and applied a linear interpolation based on the solar activity index. F10.7 between these two states within the model. ... to ...and applied a linear interpolation based on the F10.7 solar activity index between these two states within the model. …

Revised.

Lines 228-230: reformulate these sentences: ...we conducted percentage difference between SOLMAX and UBC-NOy experiments relative to SOLMAX experiment. SOLMAX experiments is with the solar UV radiation fixed at its maximum, using climatologies calculated based on the solar maximum spectrum only. This is what I understand from the explanation. Correct, if this is a misunderstanding: . . .we calculated the percentage difference between the SOLMAX and UBC-NOy experiments relative to the SOLMAX experiment. The SOLMAX experiment uses the solar UV radiation fixed at its maximum, resulting in climatologies calculated based on the solar maximum spectrum only.

It is revised to: "Figure 2 shows the impact of variable SSI as the percentage difference in ozone between solar maximum (experiment. SOLMAX) and solar minimum conditions (experiment. UBC-NOy), here relative to the results of the SOLMAX experiment.

Figure 2: Caption, please change ...Impact of SSI on ozone ... to ...Impact of SSI changes on ozone ...

Revised.

Line 253: Better describe what is shown in Figure 5. E.g.: In Figure 5, EPP-NOy in ICON-ART, shown as the differences between the UBCNOy and the BASE simulations, is compared to EMAC and MIPAS/ENVISAT v8.

Revised.

Line 258: correct ...leds ... to ...leads …

Revised.

Lines 260-261: write ...Comparison against the EMAC model …

Revised.

Bibliography

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