

Item-by-item response to all review comments

NOTE: To facilitate the evaluation of our responses, original review comments are listed first in their originals (in black), followed by **our itemized response (in blue)**. An annotated version of revised manuscript is attached.

We thank the reviewers' comments, which are in black text below. **Our response is followed (in blue).**

We thank the reviewers' comments on helping to improve this manuscript. We have made substantial modifications about the new contributions of the current study to address the reviewer's concerns as follows:

1. Novel diagnostic tool

The current paper develops a novel offline diagnostic tool of steady-state ozone (SSO) to be applied to climate models to separate the model-to-model discrepancy in QBO-ozone due to chemical and transport process.

Please refer to section 1, section 5.4 and 6.1 for further detail.

2. Improved ozone representation at negligible cost

Nudged QBOi experiments with improved linearized ozone chemistry ($\text{NO}_y\text{-N}_2\text{O-CH}_4\text{-H}_2\text{O}$) may improve QBO-ozone simulation than that without. This demonstrates that online linearized ozone (Linoz) calculation with negligible computational cost can be a useful tool for studying ozone and QBO-ozone relationship.

Please refer to section 5.3 and 6.1 for further detail.

3. Ozone damping effect on QBO

Additional nudged E3SMv2 simulations indicate that fixed ozone shown stronger QBO-temperature, indicating damping effect of ozone on QBO.

Please refer to last paragraph of section 6.1 for further detail.

Reviewer 1

The authors have provided extensive responses to the reviewer comments and have revised their manuscript accordingly. The revision is easier to follow.

Much of the description of the analysis is comprehensive and carefully presented. My recommendation is that this work may be eventually publishable if the authors revise the manuscript to be very clear about what is new from their work and what message the community should learn from this investigation. In particular, the title, abstract, and introduction would benefit from major revision to focus attention on what new can be learned from the model simulations and analysis. As can be seen from the major comments below, I was still confused about the main thrust of the investigation and about how the linear model is used.

Major comments

1. The manuscript still does not do an adequate job of setting up the goals of the project so the reader is left wondering what is the point of evaluating the linear ozone model. Is the

eventual goal to use this linear model in interactive runs or is it primarily for purpose of diagnosing ozone? The paper shows that the model with a nudged QBO and expanded range of chemical families (version 3) reproduces ozone reasonably well. The impact of ozone changes due to the QBO on stratospheric or climate variables is not presented and so the manuscript does not make a case for including Linoz as a component of an interactive model. The analysis seems mainly to demonstrate that this simplified model can reproduce results from more comprehensive studies showing that transport of ozone, transport of NO_y, and temperature dependence of ozone photochemistry are the dominant processes in the response to the QBO in different vertical regions. The manuscript does not describe any new insights into the chemistry or the impact of the ozone changes on the QBO, rather, it demonstrates that their linear model is able to capture these.

Response: The goal of this paper is to demonstrate the novel use of a steady-state ozone (SSO) metric to separate the chemical and transport impact of QBO-ozone. It is applied to nudged E3SMv2 with interactive ozone chemistry to demonstrate its applicability and further separate the QBO-ozone process with a more realistic QBO simulation.

Nudged E3SMv2 simulations with Linoz-v2/Linoz-v3 exhibit the impact of ozone change due to QBO. These set the base of the QBO-ozone impact, which is applied to SSO for impact separation. We were able to clearly separate the role of temperature, NO_y, and transport with pressure, which was still under debate in previous studies. This is added in the text, please refer to section 1, section 5.4, and section 6.1 for further detail.

There are two other new findings are of interest and further discussion added in section 6.1:

1. For one, the inclusion of NO_y-N₂O-CH₄-H₂O chemistry in online Linoz calculation in E3SMv2 shows better QBO-ozone magnitude above 10-hPa than that without. Meraner et al., (2020) demonstrated that the usefulness of linearized ozone in representing ozone due to negligible computational cost, despite its deficiency in simulating QBO-ozone magnitude. The inclusion of NO_y-N₂O-CH₄-H₂O chemistry may contribute to alleviating this issue.
2. For another, the interactive ozone (Linoz calculated online in E3SM and feedback to climate) tends to damp the QBO in E3SMv2. This is indicated by comparing QBO-temperature (Figs. 4, 5 and S8) for E3SMv2 Linoz-v2 simulation with E3SMv2 fixed ozone simulation.

Please refer to third and fourth paragraph of section 6.1 for further detail.

Overall, the SSO may be used applied to climate model simulations and chemistry climate models (CCM) to provide further insight on model-to-model deficiency. This includes the current QBO initiative (QBOi) simulations, the joint QBOi-CCMI project proposed by The QUasi-Biennial oscillation and Ozone Chemistry interactions in the Atmosphere (QUOCA). We've added this in the text. Please refer to section 6.1 for further detail.

Reference

Meraner, K., Rast, S., & Schmidt, H. (2020). How useful is a linear ozone parameterization for global climate modeling? *Journal of Advances in Modeling Earth Systems*, 12, e2019MS002003. <https://doi.org/10.1029/2019MS002003>

2. Unfortunately, even after several times reading through, I'm not sure I was able to follow some basic aspects of the model description. This makes it very difficult to evaluate the results. At line 65-66, "In this study, we use the interactive stratospheric chemistry module in E3SM (Linoz: 65 Mclinden et al., 2000; Hsu and Prather, 2009) as an off-line model ..." indicates the Linoz is used offline. But then at line 77-78 "Our primary modeling tool is the Department of Energy (DOE) Energy Exascale Earth 77 Model version 2 (E3SMv2, Golaz et al., 2022) with interactive stratospheric ozone ...". And at line 99-100 "Stratospheric ozone in E3SMv2 is calculated interactively through transport and the chemical Linoz module". Then at line 467-468, "the use of the offline Linoz model..." Perhaps part of the problem is the use of the term "interactive" since any potential ozone impact on the QBO is weakened or cancelled by the dynamical nudging.

Response: Thank you for the comments. The current study utilizes the linearized ozone module (Linoz) for two parts:

1. Online and interactive ozone calculation. Linoz is the linearized ozone module of the E3SMv2 and feedbacks on the climate, and thus we refer it as "interactive".
2. Steady-state ozone (SSO) diagnosis from offline Linoz. This is a novel use of the SSO metric that helps to separate the chemistry and transport impact of QBO-ozone.

To avoid confusion, we modified the text to refer to Linoz in E3SMv2, while solely refer to SSO when diagnosing chemical-driven ozone. Please refer to line 139-153 and line 364-367.

Need to note that although dynamical nudging is a relatively strong constraint, the ozone impact may still feedback on the climate. This is shown in E3SMv2 Linoz-v2 simulation and fixed ozone simulation (Figs. 4,5, and S8) – interactive ozone decreases QBO-temperature by around ± 1 K, indicating its damping effect on QBO. Please refer to last paragraph of section 6.1 for further detail.

Other comments

1. Please make it clear what you mean by "phase asymmetry" (e.g. line 74, line 179, etc.). Based on further reading in the manuscript and familiarity with the observations, it appears you mean the difference in the length of time and evolution of the wind change with pressure between the easterly and westerly phases. This should be defined at the outset so the reader is not wondering what asymmetry you are referring to.

Response: The "phase asymmetry" refers to asymmetry between QBO phases – a stronger and shorter QBO easterly phase and weaker and longer QBO westerly phase. Please refer to line 57 – 58 for detail.

2. (l. 326-327) Sentence beginning "This indicates ...". Since the response of column ozone is mainly driven by the winds in the lower stratosphere, this discrepancy likely indicates that the internally generated QBO is too weak there.

Response: It is revised to "Since the response of column ozone is mainly driven by the wind in the lower stratosphere, this discrepancy likely indicates that the internal generated QBO is too weak there". Please refer to line 331-332.

3. (l. 349-356) What are you trying to say here? The figure indicates poor response of ozone in the simulation with internally generated QBO. What is the "improved representation" that is referred

to?

Response: The improved representation referred to the E3SMv2 Linoz-v3 “NO_y-N₂O-CH₄-H₂O chemistry”, which had improved the deficiency in E3SMv2 Linoz-v2 simulation at around 10-hPa. To eliminate the confusion, the “improved representation” sentence is removed. Please refer to line 368-369.

4. Is anything additional learned from the convoluted calculation of the ozone that CESM2 would have if it used Linoz?

Response: The CESM2 steady state ozone calculation reflects the temperature effect on ozone. It is derived as a demonstration of the SSO on non-interactive ozone chemistry. It may also be an indication of the “would-be” temperature-ozone if Linoz were to be implemented in CESM2. To avoid confusion, we’ve revised the paper and remove the latter expression. Please refer to line 522.

Editorial comments

1. (l. 394) “the no response” -> “the lack of response”
2. (l. 427) What does “colder/warmer” mean? It’s either one or the other.
3. (l. 469) “with the with the”

Response: Revised as suggested.

Editor comments on manuscript egusphere-2024-1927 (revised version)

We thank editor for making comprehensive comments. The revision are made accordingly. The response to the comments are as follows, the lines are referring to the trackchange version.

Specific comments:

P1, L22: It is not clear what is meant with “modeled changes temperature”. Please rephrase.

P1, L25: For me it is not clear if these are detected by these changes or if these are caused by these changes.

P2, L35: Add “tropical” before “stratosphere” since this relates to the tropical stratosphere not the entire stratosphere.

P2, L38: Please rephrase the sentence. The QBO itself does not influence the chemical processes in the atmosphere rather the changed composition of the atmosphere due to the QBO is affecting chemistry.

P2, L60: “Nudging of the winds is unphysical and produces an anomalous BDC....”. Is this really true. I had a quick look at the Orbe et al. paper and to my understanding they just stat that care should be taken then SD simulations are compared.

Response: The comments are revised as suggested.

P3, L65ff: To my knowledge Linoz is providing only very basic, simplified chemistry which I guess is sufficient for climatic studies. Nevertheless, I would appreciate a statement about the general quality/accuracy of the Linoz scheme.

Response: We thank for the comment. Studies have verification the validity of Linoz in representing the ozone chemistry in stratosphere (McLinden et al., 2000), and also shown ozone response to 4xCO₂ (Meraner 2020). We’ve added these in the text. Please refer to

P3, L83 and 84 and throughout the manuscript: As already stated in my comments before publication in the discussion you should use the Copernicus style and abbreviate write Section beginning with a capital letter and abbreviate it as “Sect.” unless it appears at the begin of the sentence.

Response: Revised as suggested. All sections are abbreviated as “Sect.”

P4, L121: Were tuned ? Please specify this. What exactly has been done?

P5, L135: A reanalysis is no observation even if observations have been assimilated!

Response: Revised as suggested.

P7, L186: “QBOW”: I guess you mean here the QBO west. This abbreviation should be introduced.

Response: Thank you for the comment. The QBOW has been previously introduced. Please refer to line 335.

P8, L220: Please use here a clear writing for dates. Do you mean September 1970 to March 1972?

Response: 1970 September to 1972 March.

P9, L255: Please use the Copernicus style. Equation should be abbreviated as Eq. in the text.

Response: Revised as suggested.

P9, L256: Has the abbreviation SSO been introduced?

Response: Revised as suggested. Please refer to line 87.

P9, L266: “The center” not clear. Do you mean the center of the composite is where the NPLA shift is? Please rephrase so that it becomes clear where the center is.

Response: Yes. The center refers to the “center of the composite”. It is revised in the text, please refer to line 428.

P9, L274-275: Rephrase/Improve sentence.

Response: Revised as suggested.

P10, L287-291: Repetition of what has been said before???

Response: It refers to the temperature pattern instead of wind pattern referred before. We revised to avoid confusion. Please refer to line 449-453.

P11, L318: “The TCO patterns exhibits tri-pole pattern of anomalous low in the tropics and high in the extratropics during” Sentence not clear since something is missing here. Please correct.

Response: It referred to the reanalysis TCO, we revised as suggested. Please refer to line 503.

P11, L320: “The magnitude of the negative in QBOe”? Not clear. Please correct/rephrase.

Response: It is changed to “The magnitude of the low TCO in QBOe.” Please refer to line 506.

P11, L335: Has the abbreviation “CMZM” been introduced?

Response: It is the Concentration Monthly Zonal Mean (CMZM) product (Sofieva et al., 2023) mentioned in previous paragraph, please refer to line 291.

P12, L341: “low” -> do you mean “low ozone”? Please clearly write this.

P12, L344: Change sentence as follows: Since the nudged E3SMv2 simulation uses the Linoz-v2 scheme where the chemical species such as

P12, L347: Change to “with chemistry of NO₂-N₂O-CH₄-H₂O included”.

Response: Revised as suggested.

P12, L348: Missing parts of what?

Response: Missing ozone fluctuation between 6-hPa to 10-hPa. Please refer to line 536.

P12, L366: Correct as follows: “phase changes in the northern hemisphere.”

Response: Revised as suggested.

P14, L398: What is noisier? The temperature? Please clearly state this.

Response: The temperature is noisier. Revised as suggested.

P14, L403: Either singular or plural, thus either “like stratospheric sudden warmings” or “like a stratospheric sudden warming”. Further “stratospheric” and “sudden” need to be swapped. It should read “sudden stratospheric warming”.

Response: Revised as suggested.

P14, L418: “To further examine the variable responsible for the change, the single specie sensitivity.....” Please improve sentence.

Response: Revised as suggested.

P14, L426: Please clearly state which level.

Response: Revised as suggested.

P15, L431-432: Check sentence and rephrase. Add “that is” before controlled? What is meant with “return arm”.

Response: It is a return branch of the QBO-induced circulation. Revised in the text. Please refer to 705.

P16, L441: Similar than what? Please use clear statements.

Response: Similar temperature and w^* patterns. It is revised as suggested. Please refer to 714-715.

P15, L442: Change to “.... Similar prognostic ozone if Linoz were to be implemented.....”

Response: Revised as suggested. Please refer to line 715-716.

P14 and P15: References to the figures are given in a very confusing order. You are jumping here back and forth between the figures which makes it very hard to follow.

Response: Revised as suggested. We revised the figures to avoid jumping back and forth.

P15, L455: Here references should be given. I assume this statement is based on results from previous studies.

Response: The statement is based on the evaluation of the metrics for the current panel Figure 13a.

P16, L459ff: NH -> northern hemisphere, SH -> southern hemisphere. Please use a consistent writing.

P16, L460: Also here references should be added.

Response: Revised as suggested.

P16, L487: “less field of high wavenumbers” not clear

Response: Revised as suggested. It should be “less spectrum of zonal wavenumbers”. Please refer to line 742.

P17, 489: “with nudging” -> please rephrase

P17, L502: Check sentence and please correct.

Supplement: Check numbering of figures. Figure S7 appears twice.

Response: Corrected as suggested.

Figure captions in general:

These should start with “Figure” and the respective number followed by a colon. “Figure” is only abbreviated in the text!

anomalous -> anomaly

use a readable date formats.

Add degree sign to the given coordinates.

Figure 8 caption: OBS? Do you mean “observations”?

Technical corrections:

P2, L33: add “atmospheric” before “circulation”.

P2, L33: that -> and

P2, L55: Write “zero” instead of “0”.

P4, L104: about -> of (?)

P6, L179: QBOs -> QBO

P10, L287: tropics -> tropical

P10, L302: add “the” -> the northern

P10, L303: accordance? Do you mean “agreement”?

P10, L305: extratropics -> extratropical

P11, L307: is -> are

P11, L310: creates more -> creates a more

P11, L334: extratropics -> extratropical

P12, L345: chemistry -> chemical

P12, L354: add “being” so that it reads “being weaker”.

P12, L355: add “the” -> the E3SM-v2

P13, L367: hemisphere -> hemispheres

P13, L375: section 4 -> Sect. 4

P13, L374: equation 2 and 3 -> Eq. 2 and 3
P13, L389 and 392: correspond -> corresponds.
P14, L398: Southern Hemisphere -> southern hemisphere
P15, L439: process -> processes
P16, L483: Add "the" so that it reads "by the two models".
P16, L439: change -> changes
P16, L462: write "and" instead of using a comma.
P16, L465: Conclusion -> conclusion
P16, L467: Firstly -> First
P16, L468: dynamic -> dynamical
P16, L468: add "the" so that it reads "of the QBO".
P16, L469: delete "while the".
P16, L470: profile -> profiles (?)
P16, L 471: Delete "the"
P16, L475: difference -> different
P16, L482: degree sign missing.
P17, L488: Lastly -> Last
P17, L507 and 509: Add "the" so that it reads "the nudged" and "the QBO", respectively.
P17, L512: process -> processes
P17, L515: Delete "change".

[Response: We thank the editor's thorough comments. These are revised as suggested.](#)