

## Response to the Editor

We thank Dr. Andreas Hofzumahaus, the ACP Editor for the detailed comments and suggestions, as well as for the time and effort invested in the review process of this manuscript. We believe the revisions have strengthened the manuscript. Below we provide a detailed point-by-point response to all the comments. **The Editor's comments are shown in blue**, and our responses follow in black. The changes in the manuscript are highlighted in **red and underlined**. Page and line numbers are provided for the revised version.

### Editor's comments

Your manuscript has undergone a second review. Referee #2 is satisfied with the modifications, but Referee #1 is asking for additional revisions. Referee #1 criticizes the missing discussion of the FNR's potential dependencies on external parameters that are independent of HCHO and NO<sub>2</sub> concentrations.

I agree with Referee #1 on this point. Although the current manuscript notes in line 55 that "the FNR has inherent limitations in representing O<sub>3</sub> chemistry (Souri et al., 2023a)," these limitations are not explained and discussed either at this point or later in the manuscript. The ACP author guidelines ([https://www.atmospheric-chemistry-and-physics.net/policies/guidelines\\_for\\_authors.html](https://www.atmospheric-chemistry-and-physics.net/policies/guidelines_for_authors.html)) clearly state that the Conclusions section, in particular, must outline the limitations of the work ("Caveats and limitations: State how these affect confidence in the overall results, and where future work is needed."). Before the manuscript can be considered for publication, further revisions are therefore needed. Please pay attention to the comments given by Referee #1 and discuss the limitations of your work. In line 57, you state "Consequently, under certain conditions, FNR may misclassify O<sub>3</sub> formation sensitivity". Please explain what this means and discuss the relevance for your results, providing quantitative data where possible.

Response:

Thank you very much for the Editor's comments and suggestions, which have helped us improve the manuscript. According to the suggestions from the Editor and Reviewer 1, we have added discussions on the limitations of the FNR indicator and explained how we minimize potential biases, in the Introduction section (**page 2, lines 55-60**):

"The FNR has inherent limitations in representing O<sub>3</sub> chemistry **because it does not account for other atmospheric dimensions, such as photolysis rates and water vapor** (Souri et al., 2023, 2026). A wide transition/ambiguous range of FNR values has been reported compared with the more precise LNO<sub>x</sub>/LRO<sub>x</sub> ratio (Schroeder et al., 2017). Consequently, under certain conditions, **especially under low photolysis rates**, FNR may misclassify O<sub>3</sub> formation sensitivity. Nonetheless, FNR remains a commonly used indicator because it can be readily obtained. **In this study, we discuss the application of FNR under conditions of strong photolysis rates to minimize potential misclassification.**"

Additionally, we have added a section discussing the study limitations and future perspectives in the manuscript (**pages 18-19, lines 476-486**):

“The use of FNR indicator with satellite and ground-based observations can be readily implemented. However, FNR has inherent limitations in inferring the complex interactions among O<sub>3</sub> production, its precursors, photolysis rates, and water vapor (Jin et al., 2025; Schroeder et al., 2017; Souri et al., 2026; Yang et al., 2026). For example, during the early morning and late afternoon, weak light intensity can lead to large biases in the interpretation of FNR because O<sub>3</sub> production is less sensitive to its precursors under low photolysis conditions. In this study, we minimized the potential biases in predicting O<sub>3</sub> chemistry by using Pandora data under conditions of strong photolysis rates. This may underutilize the rich hourly observations provided by Pandora and geostationary satellites. Lin et al. (2025) developed an approach to link the FNR with O<sub>3</sub> chemistry using a steady-state O<sub>3</sub>-NO<sub>x</sub>-VOC model combined with GOES-CF simulations, and applied it to TEMPO observations. Additionally, Souri et al. (2026) optimized the OMI and TROPOMI data to investigate the daily mapping of net O<sub>3</sub> production using a deep neural network approach. A similar approach could also be applied to Pandora data to derive accurate hourly net O<sub>3</sub> production estimates.”

And in the Conclusions (page 19, lines 508-511).

“The FNR indicator can be readily obtained from both satellite and ground-based observations, enabling quick assessment of O<sub>3</sub> chemistry. However, the FNR indicator lacks consideration of other factors, such as photolysis rates and water vapor. For more precise interpretation, studies should incorporate these indicators and others atmospheric dimensions. The combination of both modeling and machine learning could also be beneficial for the interpretation.”

## References

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## Response to Reviewer 1

We thank the reviewer for further comments and suggestions, also the time and effort that he invested into the review. We believe the revisions have strengthened the manuscript. Below we provide a detailed point-by-point response to all the comments. **The reviewer's comments are shown in blue**, and our responses follow in black. The changes in the manuscript are highlighted in **red and underlined**. Page and line numbers are provided for the revised version.

### Reviewer comments

The authors have readjusted several figures and removed FNR during less photochemically active hours (including wintertime). I want to re-emphasize two important points that are not well discussed in the conclusion and introduction sections:

i) My criticism of FNR is not about errors related to how well it compares with LROX/LNOX. It is about a more fundamental issue: FNR lacks other critical dimensions, such as photolysis rates and water vapor. Light is the initiator of the ROX-HOX cycle and is controlled by factors (solar angle, aerosols, surface albedo, and overhead ozone) that are independent of HCHO and NO<sub>2</sub> concentrations. These limitations also apply to LROX/LNOX. I recently gave a talk on this topic using TEMPO results: [https://docs.google.com/presentation/d/15qGNSZyYyIiad771J6f6QpqpGnf8YbN/edit?usp=s\\_haring&ouid=105926912778719329798&rtpof=true&sd=true](https://docs.google.com/presentation/d/15qGNSZyYyIiad771J6f6QpqpGnf8YbN/edit?usp=s_haring&ouid=105926912778719329798&rtpof=true&sd=true).

I would like the authors to appreciate the fact that the magnitude of the sensitivities (dPO<sub>3</sub>/dNO<sub>x</sub> or dPO<sub>3</sub>/dVOC) is more informative than binarizing the atmosphere, and those sensitivities are heavily influenced by photolysis rates.

Response:

This study mainly focused on the application of Pandora measurements to predict O<sub>3</sub> sensitivity using the FNR indicator. We agree that FNR indicator is not perfect and still require further improvement. Here we see values in Pandora observations for its practical use in the FNR approach.

We have mentioned that the FNR indicator lacks other dimensions in the Introduction (page 2, lines 55-56):

“The FNR has inherent limitations in representing O<sub>3</sub> chemistry **because it does not account for other atmospheric dimensions, such as photolysis rates and water vapor** (Souri et al., 2023, 2026).”

And in the Conclusions (page 19, lines 508-511).

**“The FNR indicator can be readily obtained from both satellite and ground-based observations, enabling quick assessment of O<sub>3</sub> chemistry. However, the FNR indicator lacks consideration of other factors, such as photolysis rates and water vapor. For more precise interpretation, studies should incorporate these indicators and others atmospheric dimensions. The combination of both modeling and machine learning could also be beneficial for the interpretation.”**

We appreciate the reviewer for introducing the magnitude of the sensitivities (dPO<sub>3</sub>/dNO<sub>x</sub> and dPO<sub>3</sub>/dVOC). We have mentioned it in the Limitations and future scopes section. It can be seen that the GEOS-Chem simulations in our study were also able to reproduce the significant seasonal changes in O<sub>3</sub> production, with much stronger magnitude in summer than

in winter (Figure S1 in the SI). Linking the FNR indicator with the magnitude of sensitivities would be valuable and could be explored in future work.

For instance, Lin et al. (2025) developed an approach to link the FNR indicator with O<sub>3</sub> chemistry using a steady-state O<sub>3</sub>-NO<sub>x</sub>-VOC model combined with GOES-CF simulations, and applied it to TEMPO observations. Therefore, we believe that FNR data derived from Pandora observations could also serve as a useful tool for developing precursor emission control strategies for O<sub>3</sub>.

ii) FNR is not as simple as it appears. The authors repeatedly state that FNR does not require extensive modeling work. This is a big lie. Dividing two variables is straightforward. But what would be needed to translate these unitless values into physically meaningful information? A model. And a model has been used here. If the authors are confident in their model, why not use it to redesign the study and parameterize PO<sub>3</sub> as a function of light, water vapor, and HCHO and NO<sub>2</sub> concentrations? <https://acp.copernicus.org/articles/26/809/2026/>.

Response:

Thank you for this point. Indeed, we used a model, so we agree with the reviewer. To avoid confusion, we have adjusted the statement in the manuscript (page 2, lines 59-60).

“Nonetheless, FNR remains a commonly used indicator because it can be readily obtained.”

We appreciate the reviewer’s suggestion regarding the absolute O<sub>3</sub> production. The main purpose of this work is to use Pandora data, which are currently being expanded globally, to assess O<sub>3</sub> sensitivity. The reviewer’s suggestion could be considered in our future work to further improve the accuracy of Pandora based applications. Thank you again.

Additionally, we have added a section discussing the study limitations and future perspectives in the manuscript (pages 18-19, lines 476-486):

“The use of FNR indicator with satellite and ground-based observations can be readily implemented. However, FNR has inherent limitations in inferring the complex interactions among O<sub>3</sub> production, its precursors, photolysis rates, and water vapor (Jin et al., 2025; Schroeder et al., 2017; Sourì et al., 2026; Yang et al., 2026). For example, during the early morning and late afternoon, weak light intensity can lead to large biases in the interpretation of FNR because O<sub>3</sub> production is less sensitive to its precursors under low photolysis conditions. In this study, we minimized the potential biases in predicting O<sub>3</sub> chemistry by using Pandora data under conditions of strong photolysis rates. This may underutilize the rich hourly observations provided by Pandora and geostationary satellites. Lin et al. (2025) developed an approach to link the FNR with O<sub>3</sub> chemistry using a steady-state O<sub>3</sub>-NO<sub>x</sub>-VOC model combined with GOES-CF simulations, and applied it to TEMPO observations. Additionally, Sourì et al. (2026) optimized the OMI and TROPOMI data to investigate the daily mapping of net O<sub>3</sub> production using a deep neural network approach. A similar approach could also be applied to Pandora data to derive accurate hourly net O<sub>3</sub> production estimates.”

## References

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