Dear Reviewer:

We would like to thank you for your valuable feedback and constructive comments on our manuscript. We have carefully considered each of the referee's comments and suggestions and have revised the manuscript accordingly. In this response, we respond to all of the comments point to point. The referee's comments are listed below in black, our response is given in blue and the modification to the manuscript is listed in red. The page and line numbers for corrections are referred to the revised manuscript; the page and line numbers of the original manuscript remain unchanged. References relevant to the response are listed at the end of this document.

Comments:

The manuscripts is a detailed application description of the method introduced in a previous publication Mao et al 2024 (Mao, Y., Wang, H., Jiang, F., Feng, S., Jia, M., and Ju, W.: Anthropogenic NO_x emissions of China, the U.S. and Europe from 2019 to 2022 inferred from TROPOMI observations, Environ. Res. Lett., https://doi.org/10.1088/1748-9326/ad3cf9, 2024).

It shows in detail where the war in the Ukraine destroyed most of the ecomic and sozial (and human) live. The results are based on the comparison of modeled columns based on prior emissions, which are than adapted to satellite observations. The study focuses on the years 2019 (a pre-covid baseline) and the year 2022. The pandemic is included as small side note. The impact of the pandemic Ukraine's NO_x emissions was negligible for compared to the Russian invasion.

Mayor comments

According to (https://www.temis.nl/airpollution/no2col/tropomi_no2_data_versions.php, March 2025) version 2.4 or higher of the TROPOMI NO_2 data is reommended. There was a major version change in July 2022, I am not sure the version 2.3.1 (page 4 line 124) is appropriate for the presented study focusing on 2022. I recommend to double check the results using latest version of TROPOMI NO_2 data. In this context I ask for your apologies that I did not realize in the pre-review.

Response: We sincerely thank the reviewer for your rigorous review of the satellite observation version. According to the reviewers' suggestions, we have updated the satellite data. We now use the latest version of the TROPOMI NO_2 data. For the time period from 1 January 2019 to 25 July 2022, we use the v2.4.0 official reprocessed product, from 26 July 2022 to 12 March 2023 we use the v2.4.0 official offline product, and from 13 March 2023 to 26 November 2023 we use the v2.5.0 official offline product. For the remaining days of 2023, the v2.6.0 official offline product is used. All data were obtained from the TEMIS website (https://www.temis.nl). As noted by the reviewer, these versions incorporate significant updates to the Level-1b data and NO_2 processor, and they have been adopted as the operational standard, superseding all previous versions (including v2.3.1). The revised analysis confirms the reliability of our findings while aligning with current best practices. We have updated the manuscript accordingly.

Specifically, we have revised the description of the TROPOMI data version used in this study in Section 2.3 (see Lines 140-146):

In this study, we employed the most recent versions of the TROPOMI NO_2 product to provide optimal observational constraints for the inversion framework. Specifically, we used the v2.4.0 official reprocessed dataset for the period from 1 January 2019 to 25 July 2022, the v2.4.0 official offline dataset from 26 July 2022 to 12 March 2023, the v2.5.0 official offline dataset from 13 March 2023 to 26 November 2023, and the v2.6.0 official offline dataset for the remaining days of 2023. These products incorporate improved Level-1b processing and retrieval algorithms and represent the most up-to-date and consistent TROPOMI NO_2 datasets available. All data were obtained from the TEMIS portal (TEMIS, 2025).

Correspondingly, we have updated all the emission estimates in the Results section in the revised manuscript.

Minor comments

1. The war has continued for 3 too long years. How did the emissions change in the second year?

Response: Many thanks for this suggestion. We have added anthropogenic NO_x emission estimates for 2023 using the new version of the TROPOMI data as a constraint in the revised manuscript.

In 2023, anthropogenic NO_x emissions in Ukraine declined by 7.6% (±1.4%) relative to the baseline, a smaller reduction compared to 2022. This year was characterized by increased temporal variability and more pronounced regional divergence. The most substantial declines were observed in February, April, September, and December, corresponding to periods of intensified military activity and heightened energy shortages during the cold season. In contrast, emissions exceeded baseline levels in March and from May to July, likely due to the resumption of agricultural activities and the initiation of reconstruction efforts. Agricultural NO_x emissions increased by 15% (±2.7%), marking a further rise compared to 2022. Industrial emissions continued to decline significantly, with an annual reduction of 24% (±4.4%), largely driven by ongoing disruptions in the eastern conflict zones. Residential emissions remained at depressed levels (18% ±3.5%), indicating that population displacement had yet to reverse. Transport-related emissions exhibited a modest rebound in the first eight months, followed by stabilization towards the end of the year. Regionally, the eastern part of Ukraine continued to experience the largest reductions (17%), driven by industrial stagnation, destruction of energy infrastructure, and substantial population loss. In contrast, emissions in western regions declined by only 3%, reflecting greater resilience supported by industrial relocation, adaptive agricultural practices, and international assistance. Notably, eastern Ukraine experienced the lowest emission levels in January, April, and September, while June showed a smallest reduction (12%) likely linked to military mobilization ahead of counteroffensive operations. In the west, a significant reduction was observed only in February, associated with energy supply disruptions.

We have revised the Results section of the manuscript to incorporate these changes (see Lines 287–320):

In 2023, anthropogenic NO_x emissions in Ukraine declined by 7.6% (±1.4%) relative to the baseline (Fig.2 b, c, e). The most pronounced reductions were observed in February, April, September, and December. Notably, unlike the sustained emission decline throughout 2022, 2023 exhibited intermittent increases, with higher emissions than the baseline observed in March and from May to July. From a seasonal perspective, persistent energy shortages during the cold season remained a critical constraint in early spring (before March) and late autumn (after September), contributing to continued emission reductions during these periods.

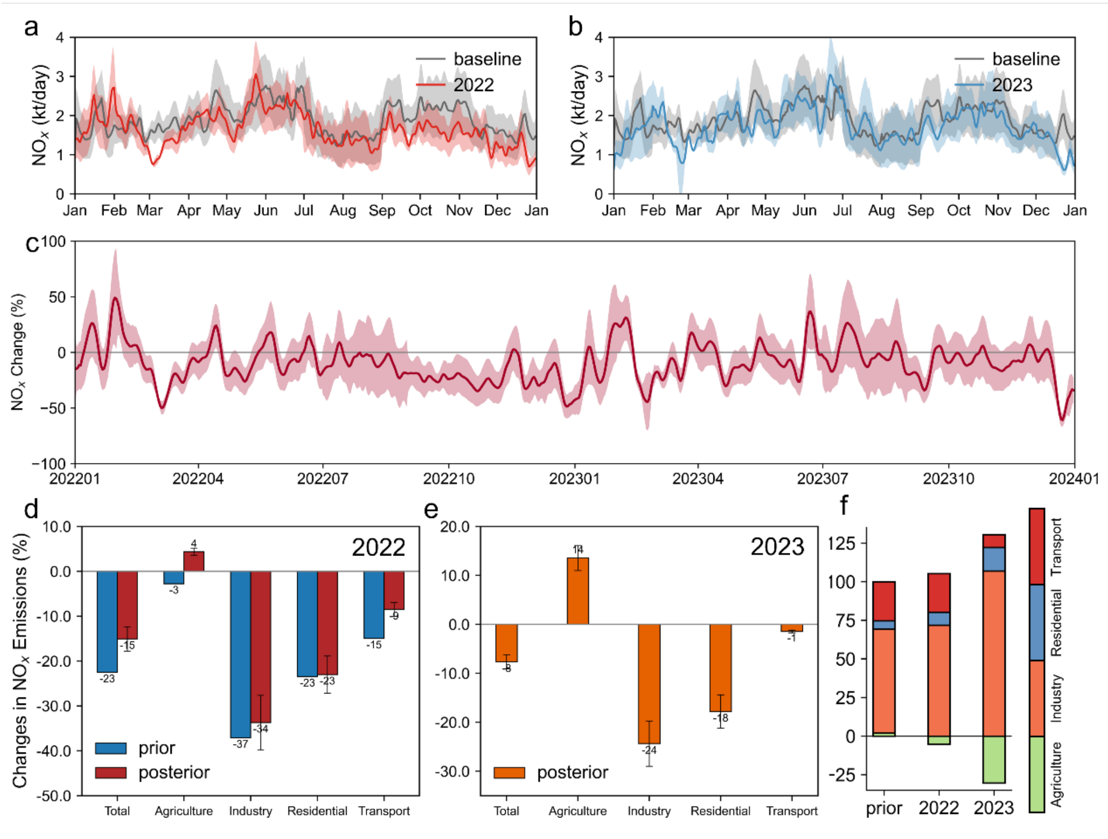

Fig. R1. Changes in anthropogenic NO_x emissions in Ukraine during 2022 and 2023 and their deviations from the baseline period. (a) Daily anthropogenic NO_x emissions in 2022 (red) and the baseline period (black). (b) Daily anthropogenic NO_x emissions in 2023 (blue) and the baseline period (blue). (c) Relative differences in daily emissions in 2022 and 2023 compared to the corresponding days in the baseline period. (d) Sectoral contributions of prior (blue) and posterior (red) emissions in 2022 relative to the baseline. (e) Sectoral contributions of posterior emissions in 2023 (orange) relative to the baseline. (f) Contribution of each sector to the total reduction in emissions in 2022 (prior and posterior) and 2023, compared with the baseline year. (Fig.2 in revised manuscript)

We examined the reductions in anthropogenic NO_x emissions across different sectors following the outbreak of war in 2022 based on both the prior and posterior estimates, as well as the sectoral changes in 2023 derived from the inversion (Fig. 2d, e), and the contribution of each sector to the total emission reduction (Fig. 2f). The inversion indicate that the industrial sector experienced the most significant impact from the war. Compared to the baseline, industrial emissions declined by 34% (±6.1%) in 2022 and by 24% (±4.4%) in 2023, accounting for 72% and 106% of the total annual reductions, respectively. These declines are comparable to those estimated from the prior inventory for 2022 and can largely be attributed to the heavy fighting and infrastructure disruption in the eastern industrial regions of Ukraine. Residential emissions also showed substantial reductions of 23% (±4.1%) in 2022 and 18% (±3.5%) in 2023. Despite contributing less to the total reduction due to their relatively smaller share of emissions, the residential sector was the only sector in 2023 that did not exhibit a notable alleviation in its reduction rate. This persistence is likely associated with the population loss. The transport sector was a significant contributor to land-based anthropogenic NO_x emissions in Ukraine, but the observed decline was not as pronounced as that observed in the residential and industrial sectors. The reduction in transport emissions may have been partially offset by increased emissions from population displacement and logistical movements. Moreover, compared to the prior inventory, the inversion suggests a smaller reduction in transport emissions in 2022. This discrepancy could be due to the underestimation of military and emergency transport activities in energy-based inventories. In contrast to the prior inventory, which suggested a 3% decline in agricultural emissions in 2022, the inversion results indicate a 4% (±0.7%) increase in 2022 and a more pronounced 15% (±2.7%) increase in 2023. This discrepancy likely arises from the limitations of statistical data used in the prior inventory, which may have underestimated additional NO_x emissions from traditional farming practices and irregular land management under war conditions. The inversion results also suggest that the increase in agricultural emissions may partly reflect an overestimation of emissions in the central and western regions due to the assumption of fixed sectoral emission allocation.

And in Lines 329–333:

During the summer of 2023, agricultural emissions were approximately 6% higher than in 2022, indicating a gradual economic recovery in the central and western agricultural regions of Ukraine one year after the outbreak of the war. In contrast, the industrial sector exhibited substantial fluctuations in its emission reductions in 2023, likely reflecting repeated military operations in the eastern conflict zones. Transport-related NO_x emissions increased by 4.3% compared to 2022, indicating a gradual recovery in domestic mobility.

For decline in different regions (Lines 351–352):

In 2023, NO_x emissions in central and western Ukraine increased compared to the baseline, while emissions in the eastern regions remained suppressed due to ongoing localized conflict (Fig. 3b).

And in Lines 354–360:

In 2023, emissions increased further across the region, reflecting Crimea's growing role as a long-term base for Russian troop deployment and logistical support. Sectoral analysis reveals varying degrees of recovery in agriculture, industry, and transportation across central and western Ukraine. In contrast, residential emissions in 2023 remained at levels comparable to those in 2022, consistent with the national trend. These findings suggest that while efforts to reestablish agricultural and industrial activity have taken hold in the rear regions of the battlefield, residential activity has yet to recover, likely due to continued population displacement.

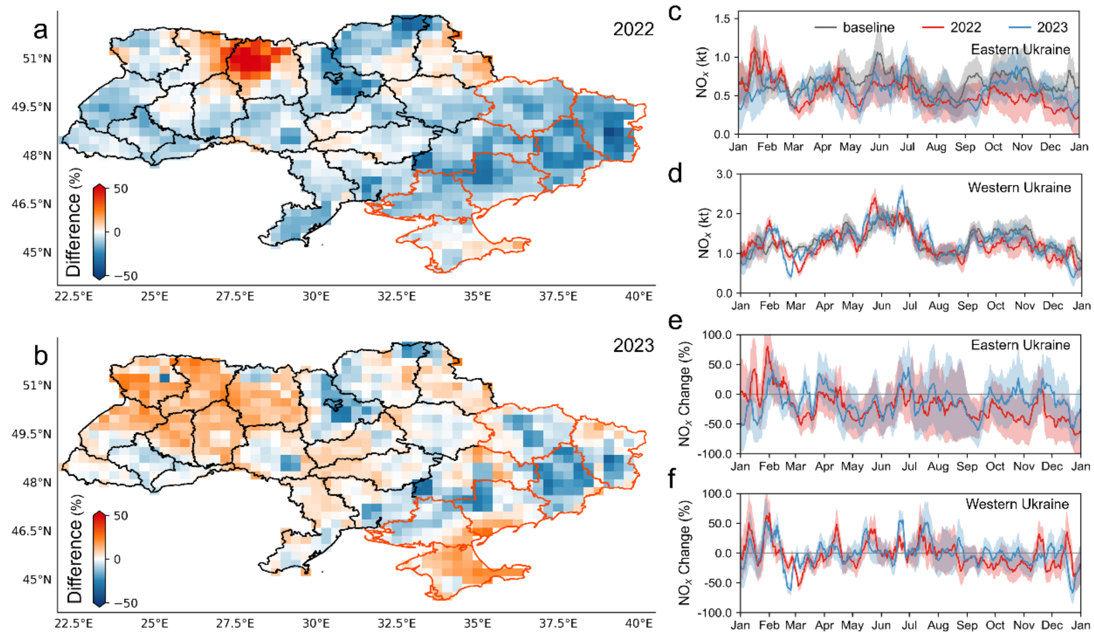

Fig. R2. NO_x emissions changes in different regions. (a~b) Spatial distributions of NO_x emissions changes in Ukraine during war in (a) 2022 and (b) 2023 relative to the baseline. Eastern Ukraine is marked with red lines, and Western Ukraine is in black. (c~d) Daily NO_x emissions in 2022, 2023 and the baseline years in (c) Eastern Ukraine and (d) Western Ukraine. (e~f) Relative changes in daily NO_x emissions in 2022 and 2023 relative to the baseline in, (e) Eastern Ukraine, and (f) Western Ukraine. (Fig.3 in revised manuscript)

And in Lines 379-389:

In 2023, anthropogenic NO_x emissions in Ukraine also exhibited a marked spatial divergence between the eastern and western regions. The Eastern Ukraine experienced a sustained emission decline of 17.0 % (±3.1%) compared to the baseline, largely attributed to industrial inactivity under Russian control, destruction of power infrastructure, and ongoing population displacement. In contrast, emissions in the Western Ukraine declined by only 2.9 % (±0.5%), reflecting greater resilience due to the westward relocation of industry, influx of international assistance, and support from adaptive agricultural practices. Seasonal trends reveal that eastern emissions reached their lowest points in January (-35.8 %±6.4%) due to exacerbated energy shortages, in April (-16.2 %±2.9%) during intensified military offensives, and in September (-31.7 %±5.7%) following a second collapse of the power grid. The smallest reduction (11.9 %±2.1%) was observed in June, likely driven by intensified military activity during Ukraine's counteroffensive. In the west, the most substantial reduction occurred in February (10.0%±1.8%) and December (22.9%±4.1%), primarily due to gas supply disruptions by Russia and regional power grid failures. Emissions in other months remained comparable to or slightly above baseline levels.

2. page 5 line 138: The inversion is performed on a Monthly basis (due to the observation gaps of the satellite). Please elaborate in more detail what this means. Does this include that the wind fields are averaged over a month. Or where the daily observations for TROPOMI and the

meteorological data used and the emission assumed to be constant for the one month.

Response: Thank you for your careful review and for raising this concern. According to reviewer 2's suggestion, we have updated our inversion framework to operate on a daily basis in the revised manuscript, instead of the previous monthly configuration. This change improves the temporal resolution of the inverted emissions and allows us to better resolve short-term variations, especially those associated with rapid wartime changes.

To address the issue of limited valid satellite pixels over Ukraine, particularly under persistent cloud cover, we adopted a 7-day moving average of TROPOMI NO_2 vertical column densities (VCDs) as observational constraints. This approach balances the need for sufficient observational coverage and the ability to retain temporal signals, as supported by sensitivity tests (see Fig. R3). We also discussed the potential limitation of this smoothing approach in capturing short-lived emission events.

Regarding model treatment, hourly NO_2 concentrations from the GEOS-Chem model were sampled at satellite overpass times. No temporal averaging was applied to the wind fields or model meteorology; we used native-resolution meteorological data (from GEOS-FP) to drive the transport and chemistry. The model outputs were vertically regridded using pressure levels to match the vertical resolution of TROPOMI, and we applied the tropospheric averaging kernel and tropopause pressure cut-off following the TROPOMI user manual recommendations.

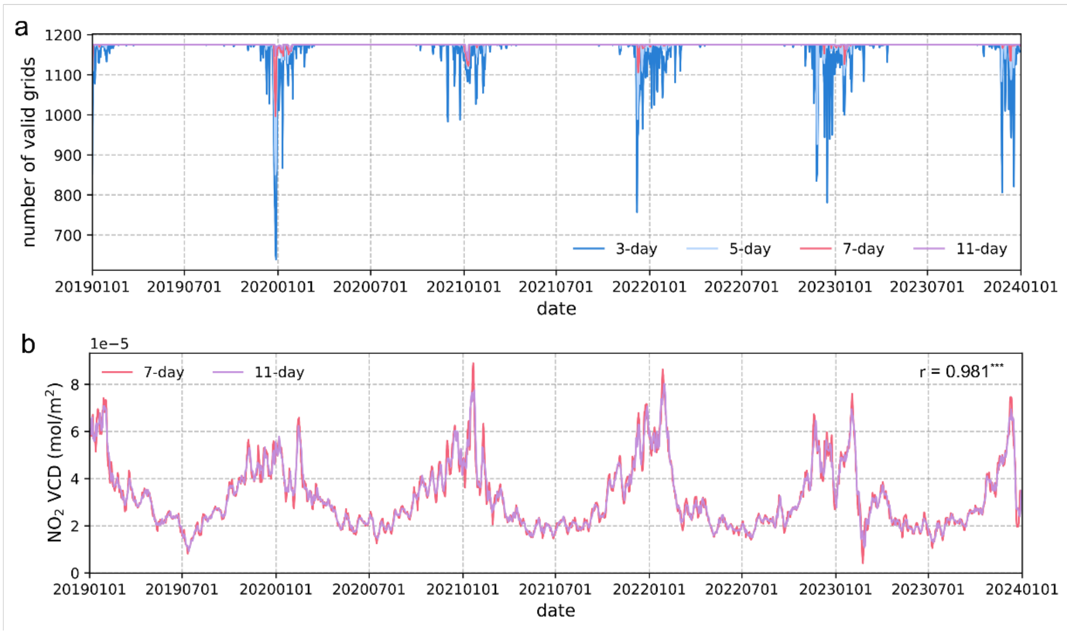

Fig. R3. (a) Number of valid TROPOMI observation grids over Ukraine from 2019 to 2023 under different moving average window lengths. (b) Comparison of daily TROPOMI NO_2 VCDs over Ukraine using 7-day and 11-day moving averages. (Fig.S1 in revised manuscript)

We have revised the relevant sections of the manuscript (Lines 164-175):

Furthermore, when using TROPOMI NO_2 VCD as observational constraints for inversion, the quality of satellite observations directly impacts the inversion accuracy. In Ukraine, the lack of sufficient valid pixels severely hampers the reliability of daily inversions. We applied a multi-day moving average window to constrain the daily simulated concentrations to address this limitation. The effectiveness of this approach has been demonstrated in previous studies (e.g., Zheng et al., 2020). We evaluated the number of valid TROPOMI observation pixels over Ukraine using different moving average window lengths during the study period (Fig. S1a). When the window size reached 7 days, the data loss significantly decreased, and the proportion of valid grid cells exceeded 90%. However, applying a multi-day average may suppress short-term fluctuations in NO_2 concentrations, potentially limiting the ability to capture rapid changes associated with wartime dynamics. We compared the NO_2 VCDs over Ukraine using 7-day and 11-day moving averages (Fig. S1b). The results showed no substantial difference between the two, but the 11-day average tended to smooth out peak concentrations more strongly. Based on this assessment, we adopted the 7-day moving average of TROPOMI NO_2 VCDs to constrain the model simulations in this study.

And Lines 183-187:

We output hourly NO_2 concentrations from the GEOS-Chem model and sampled the values corresponding to the satellite overpass times. Using pressure of each model layer, we vertically regridded the model output to match the vertical resolution of the TROPOMI satellite. Following the recommendations in the TROPOMI User Manual (van Geffen et al., 2019), based on the vertical level of the tropopause provided in the satellite product and the tropospheric averaging kernel, we integrated the tropospheric NO_2 profiles to calculate the simulated NO_2 VCD for each model grid cell.

3. P6/7 L188: The assumption if the dominant sector is really constant over time is not justified– Also the authors themselves state that it might not be correct. However I am afraid that large parts of the conclusions are based on this assumptions. Or is there any other way to distribute the NO_x emissions among the different sources?

Response: Thank you for this comment. In the revised manuscript, we have updated the method for sectoral allocation of NO_x emissions to improve the robustness of our analysis. We now utilize the sectoral distribution ratios from the updated EDGAR inventory, which extends to 2022. For all years up to and including 2022, the posterior NO_x emissions in each grid cell are distributed across sectors according to the corresponding year's sectoral ratios in the EDGAR inventory.

For 2023, due to the lack of updated sectoral data, we adopted the 2022 sectoral proportions as a proxy. This approach avoids the unrealistic assumption of a temporally invariant sector mix over the entire study period, and instead only assumes relative sectoral stability between 2022 and 2023. We explicitly acknowledge this assumption and its potential limitations in the revised text.

Moreover, our main conclusions regarding total NO_x emission trends and regional anomalies are not solely dependent on the sectoral breakdown. While we do report and discuss sectoral patterns, the key findings related to spatial and temporal variability in emissions are based on total posterior emissions, which are directly constrained by TROPOMI observations.

We have revised Section 2.4 of the manuscript to clearly explain the updated sectoral allocation method (Lines 221-223):

For sectoral emissions, we allocated grid-level totals based on the sectoral distribution ratios provided in the EDGAR inventory. For the year 2023, due to the absence of updated sector-specific data, we assumed that the sectoral proportions in 2022 remained unchanged and applied them to the 2023 total emissions.

4. P13 L339: The prior emissions are stated to be overestimated by 80%. This I s quite large has this been confirmed by similar studies?

Response: Thanks! The 80% overestimation in the original manuscript does not refer to the overestimation of the prior inventory, but rather the prior simulated NO_2 VCDs. We compared the CEDS inventory with the inverted 2019 emissions, and the relative deviation between the two was 29.7%.

In the revised manuscript, we have adopted new versions of TROPOMI NO_2 VCDs as constraints, used the EDGAR inventory as prior emissions and updated the inversion method. The modeled NO_2 VCDs using EDGAR are slightly lower than the TROPOMI v2.4.0 observations overall, but show good agreement during the winter months. Our top-down estimates are approximately 40% higher than the EDGAR inventory, primarily during the spring season. This discrepancy, however, remains within the uncertainty range reported by EDGAR.

We have revised this section in the manuscript, changing the changes in emissions to concentrations (see Lines 412-414).

Prior simulated NO_2 VCDs exhibited an underestimation of 11.6% at the national level, with the greatest discrepancy observed in the southwest and northeast regions.

Furthermore, we have added a description of the differences of emissions in prior inventory and inversion in the Uncertainty analysis (see Lines 510-511).

The inversion emissions increased by 39.9% (±7.2%) compared to the prior inventory, which is within the 50% uncertainty range of EDGAR (Crippa et al., 2018).

5. Figure 2: The Crimea peninsular in the South of Ukraine has been occupied since 2014. What causes the NO_x reduction there?

Response: Thank you for this insightful comment. We analyzed the updated results over the Crimea Peninsular to characterize emission changes and their potential drivers. Overall, anthropogenic NO_x emissions increased across the peninsular in both 2022 and 2023. The increase in 2022 was relatively modest, with slight decreases observed in western areas.

This spatial pattern is consistent with Crimea's role during the conflict period. As a key military and logistical base for Russian operations, including hosting air force infrastructure and supply chains, the region likely experienced intensified activity during the war, contributing to increased NO_x emissions from fuel combustion and transport.

We have added a discussion of this region in the revised manuscript (see Lines 352-360):

In 2022, NO_x emissions in Crimea showed a slight decrease in the western region and a modest increase in the east, primarily due to the concentration of Russian military logistics and air force operations in the eastern part of the peninsula. In 2023, emissions increased further across the region, reflecting Crimea's growing role as a long-term base for Russian troop deployment and logistical support. Sectoral analysis reveals varying degrees of recovery in agriculture, industry, and transportation across central and western Ukraine. In contrast, residential emissions in 2023 remained at levels comparable to those in 2022, consistent with the national trend. These findings suggest that while efforts to reestablish agricultural and industrial activity have taken hold in the rear regions of the battlefield, residential activity has yet to recover, likely due to continued population displacement.

Technical comments

1. p3 l 93: the sentence beginning with Meteorological data can be split into two, remove the word "while".

Response: Thank you for the suggestion. We have removed "while" and split that sentence into two sentences in the revised manuscript (see lines 106-108).

2. p5 l141: "global" instead of "g lobal".

Response: Thank you! We have corrected this typo error in the revised manuscript (see Line 177).