Author responses to reviewer comments for

Do GEMS geostationary satellite observations of tropospheric NO_2 always improve NO_x emission estimates and related air quality modelling?

Yao et al.
5 July 2026

Reviewer comments are presented in black italic text.
Author responses are indented and written in red normal font.
Revised text, as it appears in the manuscript, is indented and displayed in blue.

We sincerely thank the Editor and the reviewers for their thoughtful and insightful comments, which have greatly helped us improve the quality of our manuscript. Below, we provide detailed, point-by-point responses to each comment. Overall, our core analyses and conclusions remain unchanged, though we have made several important revisions to address the reviewers' comments and concerns. In particular, we have clarified technical details, strengthened the discussion through comparisons with previous studies, and added supplementary figures to support our interpretations. We have carefully implemented these changes while preserving the manuscript's length and improving its clarity, coherence, and readability.

Reviewer #1

Yao et al. present a comparison between a full-hourly GEMS-based inversion and a LEO-proxy inversion using the GEOS-Chem adjoint, aiming to quantify the added value of geostationary NO_2 observations for constraining monthly NO_x emissions.

The topic is timely, and the seasonal contrast between non-summer and summer is interesting. The degradation in optimizing anthropogenic emissions using NO_2 column during summer potentially suggest a strong background influence in the observations. The authors also clearly acknowledge several limitations of their analysis.

However, I have several major concerns, which need to be addressed before the manuscript can be considered for publication.

Major comments:

1. *In the abstract, the authors claim that the added value of using GEMS instead of LEO-proxy observations is "substantial", while the overall impact on monthly emission estimate is below 5.1%. While I do not deny that geostationary observations provide additional information to monthly inversions, I do not consider this level of change to be "substantial" (also shown in your Figures 2-3). Please consider rephrasing the Abstract and similar expressions throughout the manuscript.*
   Agreed. We acknowledge that the term "substantial" may overstate the magnitude of the impact. We have therefore revised the wording throughout the manuscript to adopt a more conservative and balanced tone when describing the added value of GEMS geostationary satellite observations.

2. *This work only optimizes anthropogenic NO_x. This is an important aspect of inversion setup, but is not clearly stated in the Abstract, Section 2.2 (method description), or the*

Conclusion. Please clarify this explicitly. In addition, it would be helpful to briefly explain in Section 2.2 why only anthropogenic emissions are optimized, while other sources (e.g., lightning and soil NO_x), which are generally more uncertain, are not included.

We apologize for the inaccurate statements in the original manuscript. In fact, we optimize all NO_x emission sources, as satellite observations of columnar NO_2 primarily provide constraints on total NO_x emissions. For clarification, we provide one of our configuration files below as evidence. Since our primary interest is anthropogenic emissions, we chose to present only those results in the analysis. We have corrected the relevant statements throughout the revised manuscript.

```
>------------------------------<
          FOR LADJ_EMS          :
NNEMS: ems groups implemented   : 71
Emission entries ------------> : EMS# ems_name       opt  SF_DEFAULT REG_PARAM ERROR CORR_LX CORR_LY
Emission #1                     : 1    IDADJ_ENH3_an  F    1          1         1       100      100
Emission #2                     : 2    IDADJ_ENH3_na  F    1          1         1       100      100
Emission #3                     : 3    IDADJ_ENH3_bb  F    1          1         1       100      100
Emission #4                     : 4    IDADJ_ENH3_bf  F    1          1         1       100      100
Emission #5                     : 5    IDADJ_ESO2_an1 F    1          1         1       100      100
Emission #6                     : 6    IDADJ_ESO2_an2 F    1          1         1       100      100
Emission #7                     : 7    IDADJ_ESO2_bf  F    1          1         1       100      100
Emission #8                     : 8    IDADJ_ESO2_bb  F    1          1         1       100      100
Emission #9                     : 9    IDADJ_ESO2_sh  F    1          1         1       100      100
Emission #10                    : 10   IDADJ_EBCPI_an F    1          1         1       100      100
Emission #11                    : 11   IDADJ_EBCPO_an F    1          1         1       100      100
Emission #12                    : 12   IDADJ_EOCPI_an F    1          1         1       100      100
Emission #13                    : 13   IDADJ_EOCPO_an F    1          1         1       100      100
Emission #14                    : 14   IDADJ_EBCPI_bf F    1          1         1       100      100
Emission #15                    : 15   IDADJ_EBCPO_bf F    1          1         1       100      100
Emission #16                    : 16   IDADJ_EOCPI_bf F    1          1         1       100      100
Emission #17                    : 17   IDADJ_EOCPO_bf F    1          1         1       100      100
Emission #18                    : 18   IDADJ_EBCPI_bb F    1          1         1       100      100
Emission #19                    : 19   IDADJ_EBCPO_bb F    1          1         1       100      100
Emission #20                    : 20   IDADJ_EOCPI_bb F    1          1         1       100      100
Emission #21                    : 21   IDADJ_EOCPO_bb F    1          1         1       100      100
Emission #22                    : 22   IDADJ_ENOX_so  T    1          10        1       100      100
Emission #23                    : 23   IDADJ_ENOX_li  T    1          10        1       100      100
Emission #24                    : 24   IDADJ_ENOX_ac  T    1          10        1       100      100
Emission #25                    : 25   IDADJ_ENOX_an  T    1          10        0.4     100      100
Emission #26                    : 26   IDADJ_ENOX_bf  T    1          10        1       100      100
Emission #27                    : 27   IDADJ_ENOX_bb  T    1          10        1       100      100
Emission #28                    : 28   IDADJ_ECO_an   F    1          1         1       100      100
Emission #29                    : 29   IDADJ_ECO_bf   F    1          1         1       100      100
Emission #30                    : 30   IDADJ_ECO_bb   F    1          1         1       100      100
Emission #31                    : 31   IDADJ_EISOP_an F    1          1         1       100      100
Emission #32                    : 32   IDADJ_EISOP_bf F    1          1         1       100      100
Emission #33                    : 33   IDADJ_EISOP_bb F    1          1         1       100      100
Emission #34                    : 34   IDADJ_EALK4_an F    1          1         1       100      100
Emission #35                    : 35   IDADJ_EALK4_bb F    1          1         1       100      100
Emission #36                    : 36   IDADJ_EALK4_bf F    1          1         1       100      100
Emission #37                    : 37   IDADJ_EACET_an F    1          1         1       100      100
Emission #38                    : 38   IDADJ_EACET_bb F    1          1         1       100      100
Emission #39                    : 39   IDADJ_EACET_bf F    1          1         1       100      100
Emission #40                    : 40   IDADJ_EMEK_an  F    1          1         1       100      100
Emission #41                    : 41   IDADJ_EMEK_bb  F    1          1         1       100      100
Emission #42                    : 42   IDADJ_EMEK_bf  F    1          1         1       100      100
Emission #43                    : 43   IDADJ_EALD2_an F    1          1         1       100      100
```

3. *The use of AERONET columnar NO_2 for evaluation raises some concerns, as AERONET is not primarily designed for trace gas retrievals. It would be helpful to discuss how the uncertainty and limitations of AERONET NO_2 retrievals, and how they may affect the interpretation of model evaluation results.*

Reviewer 2 also raised concerns about our reliance on AERONET NO_2 data for independent evaluation. We agree with this concern, as these datasets are retrieval products rather than direct measurements. However, we also have *in situ* measurements of surface NO_2 concentrations that support our conclusions. Following your suggestion, we have added a discussion of these uncertainties and limitations in Section 4:

We acknowledge that the robustness of this seasonal contrast between the non-summer and summer months may be influenced by uncertainties in the *in situ* measurements used for independent evaluation. In particular, AERONET columnar NO_2 measurements may be subject to biases because they are sourced from OMI retrievals. Nonetheless, Pandora NO_2 measurements are widely regarded as a benchmark reference for ground-based NO_2 observations, with a reported clear-sky precision of approximately 0.01 DU (Herman et al., 2009), and surface NO_2 concentrations are obtained from direct measurements. The consistency of our results across multiple independent datasets lends confidence to our conclusions.

4. *Figures 2-3 evaluate the two inversions across multiple temporal scales (afternoon, daytime average, and daily average). I do not see the motivation of analyzing multiple temporal scales, as the inversion only updates* ***monthly*** *emissions. Please consider simplifying the figures or clear justifying why these different temporal scales are necessary in this context.*
   Figure 2 presents a non-independent evaluation of the "LEO-proxy" and "GEMS-based" inversions, together with a comparison between them. As this evaluation serves as a critical diagnostic to verify that the 4D-Var system is functioning as intended, it is performed using the assimilated satellite observations at their native temporal resolution and therefore does not involve multiple temporal scales. In contrast, Figures 3, S5, S7, and S8 present an independent evaluation of the two inversions using multiple *in situ* measurement datasets, with model performance assessed across multiple temporal scales. To clarify the rationale for this multi-temporal evaluation, we have revised the relevant part of Section 2.4 as follows:
   To rigorously evaluate the modelled atmospheric constituents against *in situ* measurements, we sample the model at the exact time and location of each observation. Although the "GEMS-based" and "LEO-proxy" inversions only update monthly NO_x emissions, these updates are spatially heterogeneous and therefore exert non-uniform impacts on the modelled atmospheric constituents across both space and time. We then compile the paired data into GEOS-Chem grid composites at multiple temporal scales to assess the model performance driven by the two sets of inferred NO_x emissions. The temporal scales include the afternoon at 13:45 local time (KST), daytime averages (07:45 to 16:45 KST), and full daily averages. The first two correspond to the overpass periods represented by the "LEO-proxy" and "GEMS-based" inversions. This multi-temporal approach enables us to assess how the assimilated observations influence model performance both during the outside the observation periods.

5. *In Section 3.3, the GEMS-based inversion shows the same direction of correction as the LEO-proxy inversion over East Asia, but the opposite direction over North India. What drives this regional contrast? This behavior is interesting but not explained in the current manuscript. Please provide a clearer physical or observational explanation.*
   To clarify, both the "GEMS-based" and "LEO-proxy" inversions lead to widespread increases in anthropogenic NO_x emissions across the study domain, including East Asia and North India, as shown in Figures 4a3 and 4b3. The key difference is that the "GEMS-based" inversion yields larger increases over East Asia but smaller increases over North India than the "LEO-proxy" inversion, as shown in Figure 4c1. We attribute this regional contrast to the differences between the full GEMS dataset and its 13:45 KST subset. The relevant text is reproduced below for convenience:
   Figure 4c1 and Figure S17c show that in April 2021, the "GEMS-based" inversion produces higher anthropogenic NO_x emission estimates across much of East Asia,

whereas the inverse is true over North India. This spatial divergence largely mirrors the differences in the distribution of the full GEMS dataset compared to the 13:45 KST subset (Figures 4c2 and S17i). This relationship is further confirmed by a statistically significant Pearson correlation coefficient ($R = 0.49$) between the differences in *a posteriori* emission and the differences in GEMS retrievals (Figure 4c4).

6. *In Section 3.4, the explanations for changes in related species are either missing or not sufficiently accurate. For example:*

- *HCHO generally reflects VOC oxidation, and is therefore more directly controlled by the oxidation capacity (O_3 and OH).*
- *CO is primarily removed by OH, and is therefore more directly controlled by the OH.*
- *SO_2 oxidation is largely driven by OH and O_3, so it can show an inverse relationship with these oxidants.*
- *NH_3 is strongly influenced by HNO_3 availability, so increased NO_2 can enhance HNO_3 formation and thus shift NH3 partitioning and loss.*

The current explanation that these responses reflect "complex nonlinear chemistry" is too general. A more physically grounded interpretation is needed.

Agreed, and thank you for your helpful suggestions. We have replaced our previous, overly general explanation with a more specific and coherent discussion of the contrasts in modelled atmospheric constituents between the GEMS-based and LEO-proxy inversions. The revised text now reads: 'For instance, the "GEMS-based" inversion produces higher columnar and surface NO_2 concentrations across the North China Plain compared to the "LEO-proxy" inversion, while the inverse is observed over Northern India. Increased NO_2 can enhance HNO_3 formation and thus shift NH_3 partitioning to the particulate phase, resulting in similar patterns for secondary inorganic aerosols but an opposite pattern for NH_3. The uniform response of O_3 to different NO_x adjustments in the North China Plain and Northern India highlights the contrasting VOC-limited and NO_x-limited regimes governing O_3 production in these respective regions. Similar spatial distributions are evident for OH, which, together with O_3, determines the atmospheric oxidation capacity and consequently the removal of HCHO, CO, and SO_2. As a result, these species exhibit spatial patterns opposite to those of OH and O_3.'

7. *Lines 119-122. The variable c_{comp} in Eq. 1 represents a vertical column density, not a slant column density. Therefore, a priori information is inherently embedded in c_{comp}. I do not understand what the authors mean by "this process does not explicitly incorporate a priori profiles"? In fact, the influence of a priori profiles on AMF can be significant. A relevant example is Oak et al. (2024), which the authors already cite. Please clarify this point and revise the discussion accordingly.*

We apologize for the confusion. What we intended to convey was the difference between the methods of Fu et al. (2025) and Deeter (2002) for transforming model outputs into values that are directly comparable to the GEMS retrievals, as well as why we chose to use the method of Fu et al. (2025) in our study. We have revised the text to clarify this point. The revised text now reads: "We note that this process differs from the application of the MOPITT and similar averaging kernels (Deeter, 2002). This is because the DOAS method retrieves a vertical column, whereas MOPITT and similar instruments retrieve vertical profiles using a Bayesian optimal estimation framework. Consequently, there is no need, nor is it possible, to introduce an additional term representing the difference between the retrieved and a priori profiles."

Reviewer #2/3

Yao et al., compares between GEMS based and LEO based proxy emissions for the year 2021 and to investigate the utility of GEMS observations to constrains emissions.

The manuscript topic is very relevant and aims to answer very significant questions – however – there are concerns that will need to be reconciled before publication.

Major concerns:

1. *The primary objective of a GEO satellite is to derive hourly column and surface concentrations and emissions. However, this paper aims to compare between monthly emission estimates and identify if GEO is better or a LEO proxy is better. This dilutes the use of GEO observations. However, if the objective is to compare between retrieval capabilities of the instruments, there are lot of other parameters that are needed to be compared/constrained. So, I suggest the author to re-think about the objectives of this comparison.*

   We agree that the greatest value of geostationary satellite observations lies in their capability to derive hourly column and surface concentrations and emissions. Nevertheless, we believe that comparing geostationary and LEO satellite observations in the conventional application of monthly emission estimates is also meaningful, as it helps identify the strengths and potential limitations of geostationary observations before they are applied to more advanced tasks, such as deriving hourly emissions. For example, our work has revealed both the advantages and challenges of GEMS observations during non-summer and summer periods. Based on these findings, follow-on work can take a step forward by using the more reliable non-summer data to derive hourly emissions and assess the added value of such high-temporal-resolution estimates relative to conventional monthly emission estimates. This would help disentangle the benefits arising from geostationary observations themselves from those associated with advanced methodologies enabled by these observations (e.g., improved diurnal scaling factors), which have often been intertwined in previous studies. At the same time, follow-on work should take a step back to investigate the causes of the degraded performance of GEMS observations during summer. We have substantially consolidated the last two paragraphs of Section 4 to better convey these points. For convenience, the revised text is provided below:

   As stated in Section 1, only a few studies have investigated the added value of GEMS geostationary observations for top-down emission estimates (Xu et al., 2023; Park et al., 2024, 2025). We extend these efforts by providing critical insights into the benefits and technical challenges of integrating high-frequency satellite data into operational air quality management and policy-making frameworks. To ensure a controlled comparison, we optimised only monthly NO_x emissions without adjusting their empirical temporal profiles. Although this approach underuses the high-frequency information available in the "GEMS-based" dataset, we consider it necessary because the "LEO-proxy" lacks the temporal resolution to adjust diurnal profiles. Nonetheless, this approach helps disentangle the benefits arising from geostationary observations themselves from those associated with advanced methodologies enabled by these observations (e.g., improved diurnal scaling factors), which have often been intertwined in previous studies (Park et al., 2024, 2025). The seasonal contrast between non-summer and summer months revealed in this study suggests two complementary directions for future research. First, the more reliable non-summer data could be used to derive hourly emissions, and the added value of such high-temporal-resolution estimates relative to conventional monthly emission estimates could then be quantified. Second, further work is needed to investigate the factors responsible for the degraded performance of GEMS data during summer and to identify strategies for improving their utility under these conditions. Both directions would benefit from adaptive error characterisation and finer-resolution modelling.

2. *Given the results, the authors have suggested to use GEO observations for non-summer months and LEO for summer months if the community is interested in the deriving surface emissions from GEO observations. The authors have mentioned that in a single line 314 that might be attributed to photochemical sinks. I think this requires a more detailed explanation, as to what must be causing it and how.*
   We are not suggesting the use of GEO observations for non-summer months and LEO observations for summer months. Instead, our results indicate that GEMS geostationary tropospheric NO_2 observations provide added value for constraining monthly NO_x emissions during the non-summer months. In contrast, the degraded model performance observed in summer suggests that the use of GEMS observations during this season warrants further investigation before similar benefits can be established. Reviewer #1 also found this seasonal contrast interesting, and we agree that its underlying causes deserve a more detailed discussion. We discuss the sources of the added value during the non-summer months in the last paragraph of Section 3.4. In response to your comment, we have revised the last paragraph of Section 3.2 to provide a more detailed discussion of the factors contributing to the degraded summertime performance. The revised text now reads:
   We therefore speculate that the reduced model performance during the summer months is partly attributable to the markedly lower values of GEMS tropospheric NO_2 columns in summer than in non-summer months (Figures S9-S11), which are primarily due to enhanced photochemical losses under stronger solar radiation (Edwards et al., 2024; Seo et al., 2024). The low signal-to-noise ratios under low-NO_2 conditions likely make it more challenging for the 4D-Var inversion to effectively constrain monthly NO_x emissions. Additionally, lightning and other background sources likely contribute a larger fraction of these low tropospheric NO_2 columns, and their greater uncertainties than those of anthropogenic sources further complicate the inversion. The "GEMS-based" inversion assimilates a larger volume of observations with these characteristics, potentially explaining why it performs even more poorly than the "LEO-proxy" inversion, even though summertime exhibits much stronger diurnal variability (Figures S12 versus S13). In this sense, at least for our 4D-Var framework, the magnitude of the tropospheric NO_2 columns appears to play a more important role in inversion performance than the additional diurnal information provided by geostationary sampling.

3. *The authors have used LEO-proxy to compare between LEO and GEO. There is little to nothing explanation on how the LEO-proxy inversions is designed. Line 200 says: this experiment utilizes a subset of GEMS retrievals restricted to 13:45 local time (KST). But how is it done? It's important for the readers to understand how the two inversions are different from each other in their design. I also suggest the authors should consider using actual including actual LEO observations (TROPOMI/OMI) – to have some evidence on how the actual differences might look like.*
   We have added further details when first introducing the two inversions in Section 2.2 to address your concern. The revised text reads: 'By maintaining consistent parameter

settings across our experimental suite, the contrast between inversions serves as a controlled metric for evaluating the impact of high-frequency observations. We distinguish between two primary experiments: a "GEMS-based" inversion using the full hourly dataset and a “LEO-proxy” inversion that serves as a surrogate for LEO instruments (e.g., OMI, OMPS, TROPOMI) by sub-setting observations to 13:45 local time (KST). Specifically, the "GEMS-based" inversion ingests all GK2_GEMS_L2_YYYYMMDD_hhmm_NO2_[Scan area]_DPRO_ORI.nc files, whereas the "LEO-proxy" inversion ingests only those with hhmm = 0045 UTC (13:45 KST).’ In this regard, the assimilated data in the “LEO-proxy” inversion are also actual observations. This design allows us to keep all other inversion settings identical between the two inversions, thereby isolating the impact of geostationary sampling. Introducing observations from different satellite products would confound this comparison.

4. *One of the claims that the authors have listed in this manuscript is that they considered the use of independent observations to verify the columns and surface. But little explanation has been provided uncertainties and errors involved with Pandora and AERONET. I suggest the authors include a discussion on how and when Pandora and AERONET columns might be biased based on studies in the literature.*
   Reviewer 1 also raised concerns about our reliance on AERONET NO_2 data for independent evaluation. We agree with this concern, as these datasets are retrieval products rather than direct measurements. However, we also have *in situ* measurements of surface NO_2 concentrations that support our conclusions. Following your suggestion, we have added a discussion of these uncertainties and limitations in Section 4:
   We acknowledge that the robustness of this seasonal contrast between the non-summer and summer months may be influenced by uncertainties in the *in situ* measurements used for independent evaluation. In particular, AERONET columnar NO_2 measurements may be subject to biases because they are sourced from OMI retrievals. Nonetheless, Pandora NO_2 measurements are widely regarded as a benchmark reference for ground-based NO_2 observations, with a reported clear-sky precision of approximately 0.01 DU (Herman et al., 2009), and surface NO_2 concentrations are obtained from direct measurements. The consistency of our results across multiple independent datasets lends confidence to our conclusions.

Minor concerns:

1. *The current discussion speaks solely about the results observed in this paper. However, I think – the authors need to include literature and prior studies relevant to GEO/LEO based inversions and show a comparison between how their work might have similar/different results and have explanations for them.*
   Agreed. We have substantially consolidated the last two paragraphs to better highlight how our work differs from previous studies by demonstrating the added value of GEMS geostationary satellite observations for top-down emission estimates. Please refer to our response to your Major Concern 1 above for details of these revisions. In addition, following your suggestion below, we now discuss how the rebound in anthropogenic emissions in 2021 relative to the COVID-19 lockdown period in 2020 contributed to the widespread increases in the optimized emissions, and we cite previous inversion studies that reported similar findings. We hope these revisions better position our work within the context of the existing literature.

2. *Figure 6 currently shows just the simulated NO_2 column and surface concentrations after the inversions are implemented. I suggest the use of observations (both column and surface) overlayed on these maps to show how well they match with the observations. I feel the authors chose to not include them in the same figure to avoid crowding, in that case they can include an overall annual mean or a few monthly mean figures to understand how the actual improved columns and surface compare against the observations (column and surface).*
   Thank you for your suggestion. Figure 6 actually shows absolute and percentage **differences** between column and surface concentrations of modelled atmospheric constituents (NO_2, O_3, OH, CO, HCHO, SO_2, NH_3, and secondary inorganic aerosols) as driven by the "LEO-proxy" and "GEMS-based" inversions in April 2021. In this regard, we do not think it would be appropriate to overlay *in situ* observations on these maps. Instead, following Reviewer #1's suggestion, we have expanded the discussion to clarify the underlying reasons for the contrasting spatial patterns shown in Figure 6. We discuss the model performance against *in situ* measurements in the subsequent paragraph describing Figure 7.

3. *The authors suggest having conducted inversions for the 12 months, but all the figures are for the representative month of April 2021. The have shown the GEMS based NO_2 retrievals for 2021 for the 12 months in figure S11. I would suggest the authors to include a panel for inversion (a posteriori – a priori) for all 12 months. May be this will explain why they chose April as the representative month.*
   Agreed. We have now added Figures S14-S16, which present the spatial distributions of the emission adjustments made by the "LEO-proxy" and "GEMS-based" inversions, as well as the differences between their respective *a posteriori* monthly NO_x emission estimates. Table 1 also provides a concise summary of these results. April was selected as an illustrative example for the sake of brevity and because it allows us to examine how several key atmospheric constituents that are closely coupled to NOx emissions respond to the contrasting magnitudes of emission increases produced by the two inversions over North China Plain and Northern India. We have now clarified these points in the opening paragraphs of Sections 3.3 and 3.4.

4. *Figure 7 shows and Figure S13 shows NO_2 column and surface biases for North China Plain and Northern India. NCP shows positive biases for column and negative biases for the surface while we see negative biases for both column and surface for northern India. Is there an explanation for that?*
   Thank you for pointing this out. The contrasting bias patterns over the North China Plain and Northern India likely reflect different sources of model error. We assume that the negative biases found for both column and surface NO_2 over the North China Plain indicate that NO_x emissions remain underestimated, even after the inversions. This is likely associated with the rebound of anthropogenic activities in 2021 compared with the COVID-19 lockdown period in 2020, which may not have been fully captured by the inversion framework. In contrast, Northern India exhibits both positive and negative biases in column NO_2, whereas the surface NO_2 biases remain consistently negative. This discrepancy could arise from uncertainties in vertical mixing, boundary layer processes, or the vertical allocation of NOx emissions, rather than from uncertainties in emission magnitude alone. However, these processes were not optimized in the present study.

5. *2021 was one a COVID lockdown year in both India and China. There was a significant drop in anthropogenic NO_x emissions from traffic, which is probably observed by the satellite and ground-based instruments, but not by the model. I think the authors need to include a paragraph explaining this phenomenon.*

   Agreed. We have revised the beginning of the second paragraph in Section 4 as follows: "During the non-summer months (September to May), we find that both inversions yield widespread increases in NO_x emissions. Given that our *a priori* anthropogenic NO_x emissions are based on 2020, these increases likely reflect the rebound of anthropogenic activities in 2021 relative to the COVID-19 lockdown period in 2020, as also reported in other inversion studies (Abeed et al., 2025)."