April 1, 2026

Response to reviewers
Ms. No.: egusphere-2025-6175
Atmospheric Measurement Techniques (AMT)

Please find attached our response to the reviewers' comments on the manuscript titled "Uncertainty assessment of TROPOMI NO_2 over Europe using ground-based remote sensing observations" by F. Cifuentes, H. Eskes, A. Piters, J. Gomez, J. Douros, G. Pinardi, M. Friedrich, E. Dammers, M. Gebetsberger, and F. Boersma.

We thank the reviewers and the editor for their constructive feedback and valuable suggestions. Their input has helped us significantly improve the manuscript. We have carefully reviewed all comments and responded to them below.

Sincerely,

On behalf of all co-authors
Felipe Cifuentes
PhD Student
Royal Netherlands Meteorological Institute (KNMI)
Wageningen University & Research (WUR)
Email: felipe.cifuentescastano@knmi.nl

Response to Anonymous Referee #1

We thank the reviewer for the positive and encouraging evaluation of our manuscript. The suggested minor revisions have been carefully addressed, and our detailed responses are provided below.

Minor revisions

1. One of the main conclusions of the paper is that the uncertainty assessment is too optimistic and that the differences between ground-based and satellite observations exceed the total expected uncertainties. In line 562 the authors state: "These results suggest that the uncertainty estimates for the individual instruments or the representation errors derived in this study may be somewhat optimistic. Alternatively, the discrepancies could indicate the presence of additional sources of uncertainty that have not yet been accounted for in the current analysis." Could the authors further discuss, possibly with examples (e.g. in the conclusion section), what aspects of the uncertainty estimates may have been underestimated, and how? In addition, could they elaborate on potential unaccounted sources of uncertainty not included in this study, and provide recommendations for future studies.

Response:
We have added the following statement starting on Line 686.

> *"For example, residual errors may still arise from the representation uncertainty. Due to the limited spatial coverage of our high-resolution CTM simulations, which are restricted to the Netherlands domain, the impact of sub-pixel variability within a TROPOMI pixel was estimated only for the De Bilt station and subsequently generalized to the other stations included in this study. However, station-specific geographical and emission characteristics may lead to different representation uncertainty estimates. We therefore strongly recommend estimating this uncertainty parameter individually for each station when the necessary information is available. In addition, one aspect not addressed in this study is the directional sampling of the ground-based instruments (MAX-DOAS and Pandora operating in sky-scan mode). At most stations, the viewing azimuth angle (VAA) remains fixed, which limits the ability to characterize the horizontal distribution of NO_2 around the measurement site. Dual scan MAX-DOAS observations that vary the VAA can better capture this horizontal variability and thereby improve comparisons with satellite measurements (Dimitropoulou et al., 2020). In addition, the uncertainty estimates for individual TROPOMI retrievals rely on simplified assumptions regarding errors in surface albedo and cloud parameters used as inputs to the retrieval algorithm. These assumptions are likewise approximate and could be refined. Moreover, errors in albedo and cloud properties are treated as uncorrelated contributions, whereas in reality they exert a correlated influence on NO_2 retrievals, an effect that is only partially accounted for in the current methodology."*

2. Concerning the different temporal sampling, in line 352 the authors state: "For temporal alignment, MAX-DOAS and Pandora observations are averaged within a 1-hour window (±30 minutes) centered on the TROPOMI satellite overpass time." Doesn't this choice play a role in the calculated differences? Can the authors quantify this effect for a set of reasonable temporal averaging windows and/or better justify their choice?

Response:

We have investigated the impact of the temporal averaging window used in the temporal collocation. Specifically, we tested several averaging windows (e.g., 10 (±5), 30 (±15), and 60 (±30) minutes) to assess their influence on the calculated differences. We find that the choice of averaging window has a moderate impact on the results and does not significantly affect the overall conclusions of the study. Based on this analysis, we retain the ±30-minute window as a reasonable compromise between temporal representativeness and data availability. This analysis has been added to the manuscript (Line 365) and is illustrated in Figure A4 in the Appendix.

> *"Note that the choice of time window influences both the number of collocations and the associated comparison errors. As illustrated in Figure A4, the difference between MAX-DOAS MMF and Pandora DS observations, after subtraction of the stratospheric component, decreases when the time window is reduced from 60 to 10 minutes; however, approximately half of the coincident observations are lost. Therefore, a 1-hour time window is selected to preserve a sufficient number of collocations for robust statistical evaluation."*

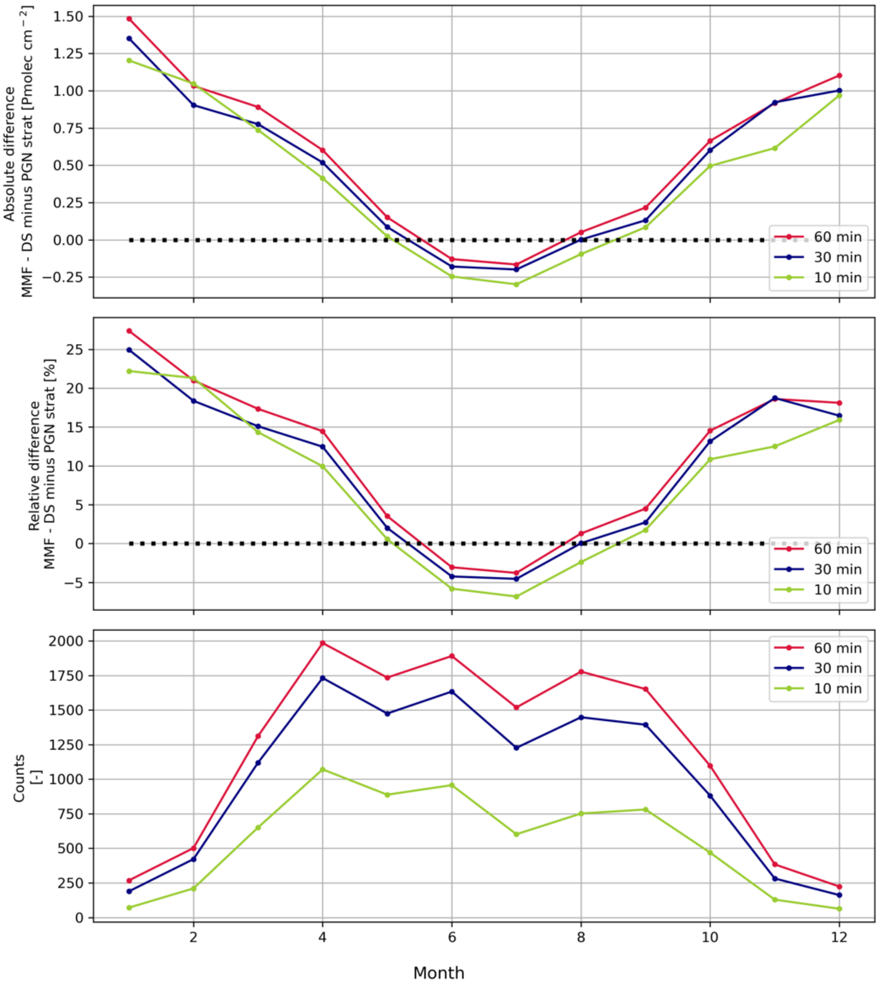

Figure A4. Differences between MAX-DOAS MMF NO_2 tropospheric columns and Pandora direct-sun observations (with the PGN stratospheric component subtracted) as a function of the time window used for temporal alignment at the Bremen station for the period 2018–2024.

3. Regarding spatial representation errors: you assess these in the Netherlands to be up to 6%. How applicable is this estimate to other sites? Can the authors elaborate on the factors that may influence this estimate, particularly in regions with different geographical or emission characteristics? Do you have an idea, based on the literature, of how much higher this variability could be?

Response:
We have added the following statement starting on Line 464.

> *"Indeed, the magnitude of representation error is strongly dependent on site-specific emission patterns and geographical characteristics, both of which determine the strength of horizontal NO_2 gradients within a satellite pixel. Stations located near strong emission sources, such as urban centers, industrial facilities, or major transportation corridors, often experience pronounced spatial variability in NO_2 concentrations. This effect has been illustrated by Pinardi et al. (2020), who showed substantial variability in subpixel horizontal gradients across several locations worldwide and quantified their impact on comparisons between ground-based and GOME-2A and OMI satellite retrievals. Topography can further amplify these gradients. For example, at stations such as Innsbruck, which is situated within a narrow Alpine valley, atmospheric pollutants can become confined by surrounding mountainous terrain. Under stable meteorological conditions, this confinement may lead to the accumulation of pollutants in the urban basin while adjacent areas remain comparatively cleaner. As a result, strong spatial contrasts in NO_2 concentrations can develop over relatively short horizontal distances, increasing the representation error when comparing local ground-based observations with satellite pixels that average over tens of square kilometers. Also, coastal stations may exhibit representation errors arising from heterogeneous surface types within a single satellite pixel. For instance, a TROPOMI pixel covering the region around Thessaloniki may include both land and sea surfaces. Because emission sources and atmospheric chemistry differ substantially between these environments, the resulting spatial gradients can also be significant."*

4. Figure7: Please include a description of all lines and colors shown in the different panels. What does the gray line represent? What is shown in the middle panels?

Response:
We have modified the caption of Figure 7 as follows:

> *"Figure 7. Monthly mean comparison of tropospheric and total NO_2 ground-based observations. The upper panels show MAX-DOAS MMF tropospheric columns (MMF, red), Pandora sky-scan tropospheric columns (Sky, blue), Pandora direct-sun tropospheric columns obtained by subtracting the stratospheric component from the Pandora climatology (DS minus PGN strat, green), and Pandora direct-sun total columns (DS, gray). The middle panel shows the relative differences between Pandora direct-sun tropospheric columns (DS minus PGN strat) and MAX-DOAS MMF (red) and Pandora sky-scan (blue) tropospheric measurements. The lower panels show the number of collocated observations for each analyzed station."*

5. **5.** Can the authors comment on the overall scalability of their findings beyond Europe? What are the expected issues outside this domain, for example, in much more polluted regions or at high-altitude sites?

Response:
We have added the following statement starting on Line 769.

> *"Although the analysis presented in this study focuses on the European domain, primarily due to the availability of a long-term alternative TROPOMI product with an improved retrieval, the conclusions are expected to be broadly applicable to other regions. In particular, our results highlight the importance of improving the spatial resolution of the a-priori profiles used in satellite retrievals. Replacing the standard profiles derived from TM5 with higher-resolution information can substantially enhance the representation of localized emission hotspots and horizontal gradients in trace-gas columns. Such improvements lead to better agreement between satellite-derived columns and ground-based remote-sensing measurements, and we therefore recommend implementing higher-resolution a-priori information whenever feasible. Furthermore, the methodologies described here for estimating both vertical and horizontal representation errors are transferable and can be applied in other regions or observational networks, provided that high-quality, high-spatial-resolution model simulations are available. Finally, the seasonal dependence of the errors identified in this study is likely to differ among regions; further investigation at regional and site-specific scales is required to fully characterize these seasonal effects and to determine how the uncertainties identified here translate to other geographical contexts."*

Response to Anonymous Referee #2

We thank the reviewer for the positive evaluation of our work and for the constructive suggestions. All minor comments have been carefully addressed, and the corresponding changes are described in the responses below.

Minor revisions

1. Introduction: The introduction is well written and provides good context. However, in line 26, I recommend revising the statement to emphasize NO_2 as a key indicator for emissions and air quality, including its role in ozone and SOA formation. The current wording may unintentionally suggest that NO_2 observations are primarily used for broader ecosystem studies rather than their central importance in air quality applications.

Response:
We have revised the first paragraph of the Introduction to explicitly emphasize that NO_2 is a key indicator of anthropogenic emissions and air quality. In addition, the discussion of ecosystem impacts has been moved later in the paragraph so that it is not the primary framing. The revised paragraph now reads as follows:

> *"Nitrogen oxides (NOx = NO + NO_2) are major air pollutants. They are primarily emitted as nitric oxide (NO) from combustion processes and are rapidly converted to nitrogen dioxide (NO_2) in the atmosphere through reactions with ozone (O_3). NO_2 poses risks to human health and environmental stability (de Vries, 2021) and serves as a widely used tracer for anthropogenic emissions from sources such as transportation, power generation, and industry. In addition to its direct impacts, NO_2 plays a central role in atmospheric chemistry, contributing to the formation of ground-level O_3 and secondary organic and inorganic aerosols (Seinfeld and Pandis, 2006), both of which significantly degrade air quality. NO_2 also contributes to acid rain and nitrogen deposition, which can affect terrestrial and aquatic ecosystems (Clark et al., 2013). Consequently, monitoring NO_2 is essential for air quality assessment, emission monitoring, and the development of effective mitigation policies to protect public health and the environment."*

2. Line 305: During the representativeness error estimation, the description of the displacement of the 4 × 4 grid is unclear. It is not evident whether the ground monitor is assumed to move within the same fixed grid box or whether multiple grid box combinations are used while keeping the ground monitor location fixed. Please clarify this description to avoid ambiguity. Additionally, the rationale for comparing the results with an OMI-sized pixel is not clear and should be further justified.

Response:
Thank you for pointing out the ambiguity. In our method, the ground-based station location is kept fixed, while the 4 × 4 model-pixel box is systematically shifted around it to represent the possible relative alignment between the TROPOMI pixel footprint and the station location. The representativeness error is then estimated from the variability across these configurations. We have revised the text to clarify this point. The updated description now reads:

> *"The bounding box was initially positioned such that it contained the model pixel whose coordinates coincide with each ground-based station. We then calculated the mean concentration over the 4 × 4 grid at a typical TROPOMI overpass time (13:30 LT) and estimated the error relative to the single model pixel corresponding to the station location. To emulate the quasi-random offset between TROPOMI pixel footprints and the station location, the 4 × 4 box was systematically shifted while keeping the station coordinates fixed, so that the station occupied each of the 16 pixels within the box. Finally, for each day, we computed the root-mean-square error (RMSE) across all 16 configurations to quantify the representativeness error."*

On the other hand, the reason for repeating this procedure with an OMI-sized grid box is to assess how a coarser satellite footprint affects the estimation of horizontal representativeness errors. This is stated in line 325.

> *"By comparing OMI-equivalent aggregated satellite columns to ground-based measurements, we aim to assess how the coarser spatial resolution of OMI, compared to TROPOMI, affects the representation of horizontal gradients and the consistency between satellite and ground-based observations."*

3. Line 350: Please clarify whether the spatial collocation accounts for the relative location of the ground instrument within the satellite pixel. Specifically, is any weighting applied based on the instrument's position within the pixel, or are contributions from neighboring pixels considered when the instrument is located near pixel edges or corners? This is particularly important for NO_2, where strong spatial heterogeneity can significantly influence the comparisons. Additionally, regarding the 1-hour collocation window, did you assess the potential influence of temporal mismatch? Ground-based monitors record data over every few seconds, while, given the TROPOMI pixel size (~6.5 × 5.5 km) and typical wind speeds (~5 m/s), an air parcel would take approximately 15–20 minutes to cross the pixel. This temporal factor may affect the representativeness of the comparison.

Response:
No weighting was applied in this study to account for the instrument location within the TROPOMI pixel. We acknowledge that this may influence the results. A detailed discussion of the temporal collocation strategy, including the impact of different time windows, is provided in our response to Reviewer #1 (Comment 2), to which we kindly refer the reviewer.

4. In Figure 4, the color scale is labeled as 'NO_2 total column' which appears to be incorrect. Additionally, the figure caption states that it represents 'Observation minus forecast for the geometric vertical columns (slant column divided by the geometrical AMF).' This procedure should be clearly explained at the beginning of Section 3.1 to avoid confusion. It would also be helpful to include a statement clarifying that when the CTM simulation of the stratospheric NO_2 column achieves close agreement with the TROPOMI slant columns over clean oceanic regions in assimilation, the difference between the TROPOMI total SCDs and the assimilated stratospheric SCDs is effectively treated as the tropospheric SCD within the TROPOMI field of view. This clarification will help readers better understand the methodology and Section 4.1.

Response:

Figure 4 presents the difference between geometric vertical columns derived from TROPOMI observations and those forecast by the TM5-MP model. As correctly noted by the reviewer, in clean remote regions, these differences are expected to be dominated by the stratospheric contribution. The color bar label in Figure 4 has therefore been revised to "NO_2 geometric column difference" for clarity.

We have also added the following statement at the beginning of Section 3.1 (line 284):

> *"In the TROPOMI retrieval, the separation of the total SCD into stratospheric and tropospheric components is performed using a data assimilation system. When the CTM simulation of the stratospheric NO_2 column closely matches the TROPOMI SCDs over clean oceanic regions during the assimilation, the difference between the observed total SCDs and the assimilated stratospheric SCDs is effectively interpreted as the tropospheric SCD within the TROPOMI field of view."*

5. Line 380, please refer to it as stratospheric NO_2. Are there any observational error estimates or studies that show the latitudinal variation of this column? It may be worth citing those efforts.

Response:

We agree and have clarified, as suggested by the reviewer, that the statement refers specifically to stratospheric NO_2 (line 391).

We have also expanded the discussion starting in line 395 to include references addressing the latitudinal variability in column errors. The revised text reads as follows:

> *"Rijsdijk et al. (2025) attribute this behavior to elevated stratospheric NO_2 concentrations in the Northern Hemisphere, which amplify absolute errors. The uncertainty of the stratospheric NO_2 column further depends on the quality of the data assimilation and the observation geometry, both of which vary with latitude and season (van Geffen et al., 2020, 2024). Larger retrieval uncertainties and modeling deficiencies in NO_2 simulations during winter have also been reported by Douros et al. (2023). Moreover, polar regions are not observed during winter due to the absence of sunlight, resulting in an accumulation of model biases over the dark pole, further degrading stratospheric column estimates at high latitudes in late winter. TROPOMI stratospheric NO_2 is routinely evaluated against NDACC ZSL-DOAS measurements, demonstrating agreement within 3% across seasonal and latitudinal variations (Lambert et al., 2025)."*

6. Lines 385–390, please provide lower and upper limits of OmF differences in percentage. At high altitudes, the stratospheric column is larger, and the absolute differences could be highest, but it would be useful to show the percentage differences in high-latitude regions during winter and early spring also large compared to other unpolluted regions.

Response:

We have estimated the percentage error in the stratospheric component over the remote clean region of the Atlantic (highlighted by the red square in Figure 4 of the main manuscript) as a proxy for high-latitude errors. Absolute and total errors were then calculated for different months as follows.

Stratospheric bias		
Month	Absolute [Pmolec/cm^2]	Relative [%]
Jan	-0.13	-9.84
Feb	-0.10	-7.25
Mar	-0.06	-4.29
Apr	-0.02	-1.8
May	-0.02	-1.77
Jun	0.03	1.8
Jul	0.01	0.41
Aug	-0.00	-0.02
Sep	-0.01	-0.6
Oct	-0.03	-2.47
Nov	-0.09	-6.32
Dec	-0.15	-11.41

Please note that a negative error in the observation minus forecast is interpreted as a positive bias in the stratospheric partition. We have included in the manuscript the following statement to discuss the percentual values, starting in Line 417.

> *"The stratospheric bias shows a clear seasonal pattern, with errors of 9% in winter, 3% in autumn and spring, and approximately -1% in summer."*

7. In Section 4.1, there appear to be few novel outcomes beyond what is already known, although some seasonal analyses are presented. The influence of tropopause seasonality, which can be strong, is not discussed. It would be helpful to quantify the resulting errors and stratospheric absolute values, potentially using observations. I also suggest examining the background Pandora Direct Sun (DS) total NO_2 measurements, which typically represent the stratospheric NO_2 contribution. These data could be used to validate the TROPOMI stratospheric NO_2 columns and to better assess the associated uncertainties in the TROPOMI observations.

Response:
We thank the reviewer for these constructive suggestions. The tropopause height is derived from ECMWF temperature profiles and will indeed depend on season, but also on local dynamic variability around the tropopause. The retrieval L2 files contain a tropopause level index, from which the tropopause pressure can be computed. This is also variable, but consistent with the TM5-MP model. On average, concentrations of NO_2 around the tropopause are low compared to the boundary layer and the stratosphere, but indeed changes in the tropopause level cause changes in tropospheric NO_2. A dedicated analysis of this effect is beyond the scope of the present study.

As for the validation with ground-based observations, routine validation of the TROPOMI product is conducted via the Validation Data Analysis Facility within the S5P Mission

Performance Centre. Stratospheric NO_2 retrieved from TROPOMI observations is evaluated against measurements from NDACC ZSL-DOAS stations. Global validation statistics indicate an agreement between datasets of 3%. But ZSL-DOAS has intrinsic uncertainties that may be larger than the TROPOMI uncertainty. A uniform bias is not relevant for the tropospheric column. The TM5-MP column is adjusted over clean regions using the TROPOMI observations. This is an effective way of removing biases. What we discuss in section 4.1 are regional/local biases, especially relevant for North-Western Europe

8. Line 417: I would describe the field as more spatially homogeneous rather than seasonal, also the scale is dominated by the highly polluted northeast areas.

Response:
Thank you for the comment. In the sentence "At seasonal scales, the NO_2 VCDs around the Cabauw station are relatively homogeneous," we intended to convey that, compared to day-to-day variability, spatial gradients become weaker when considering seasonal averages, leading to a more homogeneous NO_2 field. To clarify this point, we have revised the wording as follows:

> *"When considering seasonal averages, the NO_2 VCDs around the Cabauw station show weaker spatial gradients than those observed on day-to-day timescales, leading to a relatively homogeneous spatial distribution."*

9. Table 4: Are the smaller representation errors in winter compared to summer due to the longer lifetime of NO_2 during winter and the resulting weaker spatial gradients (more homogeneous) within the TROPOMI pixel size?

Response:
As suggested by the reviewer we have added the following statement starting in Line 458:

> *"Note also that errors are smaller in winter than in summer, which can be attributed to the extended lifetime of NO_2 during winter, resulting in a more spatially homogeneous NO_2 field with reduced concentration gradients within a TROPOMI pixel."*

10. Figure 6, in x-axis, please either say [uniteless] or remove [ ].

Response:
As suggested, the square brackets ([ ]) have been removed from the x-axis label in Figure 6.

11. Line 500: The longer lifetime of NO_2 in winter is generally expected to produce more spatial homogeneity in longer-term datasets, rather than pronounced inhomogeneities within typical TROPOMI satellite pixels. However, this does not appear to explain the winter high bias observed in MAX-DOAS MMF. As shown in Figure 7, the Pandora Direct Sun (DS) measurements are often viewing away from regions with high NO_2 columns at the TROPOMI overpass time. I recommend adding a column in Table 1 listing the Pandora Sky Scan (SS) azimuth and MAX-DOAS viewing azimuth for each instrument, as this may help better interpret the results. Additionally, including similar figures for Bremen and

> Thessaloniki in the Supplement, showing MAX-DOAS viewing azimuth together with the seasonal mean DS viewing direction based on solar azimuth, would be helpful. Also the horizontal footprint of the MAX-DOAS and DS is different.

Response:
The following statement was removed from the manuscript.

> *"In addition, MAX-DOAS exhibits a higher sensitivity to horizontal inhomogeneities along the instrument line of sight. In winter, NO_2 fields typically show a stronger vertical stratification and horizontal heterogeneity. Reduced solar heating produces a shallower, more stably stratified boundary layer with limited mixing, while the lower photochemical activity increases the NO_2 lifetime. These factors allow emissions to accumulate and enhance spatial contrasts, leading to more pronounced wintertime inhomogeneities."*

Instead, we have expanded the explanation of the highest biases in winter as follows (Line 531).

> *"The apparent overestimation of tropospheric VCDs derived from MAX-DOAS measurements in winter, relative DS measurements from which model stratospheric column contributions have been subtracted, can be partly attributed to a selection effect. During winter, significantly fewer MAX-DOAS and DS observations are valid, as indicated by the observation counts in Figure 7. This reduction is mainly due to more frequent overcast conditions and lower light levels. Consequently, the number of coincident observations is reduced, which limits the robustness of the statistical analysis in winter. In addition, we find that the quality control applied to the FRM4DOAS tropospheric NO_2 VCD retrievals from MAX-DOAS measurements tends to favor conditions with elevated NO_2 concentrations during winter. As illustrated in Figure A6, MAX-DOAS NO_2 retrievals using a geometric approximation increase in December from 7.7 to 8.9 Pmolec/cm^2 (approximately 15%) when MAPA flagging is used as a constraint, compared to retrievals without flagging. Furthermore, differences in viewing geometry between ground-based instruments may lead to the sampling of different air masses, thereby affecting the comparisons. The importance of consistent viewing directions between MAX-DOAS and Pandora instruments has been highlighted by Bae et al. (2025), who reported an improvement of approximately 10% in agreement, expressed as the mean relative difference (MRD), when viewing geometries were better aligned. As an illustrative example, we consider the MAX-DOAS station in Bremen, which operates with multiple viewing azimuth angles (VAA). Restricting the analysis to a single viewing direction can substantially affect the comparison with other ground-based instruments (see Figure A7). In particular, larger discrepancies are observed when using observations at a VAA of 180 °, compared to those at 270 ° and 295 °."*

In response to the reviewer's suggestion, we have included an additional figure in the appendix (now Figure A7) that illustrates the impact of varying viewing directions for the MAX-DOAS station in Bremen.

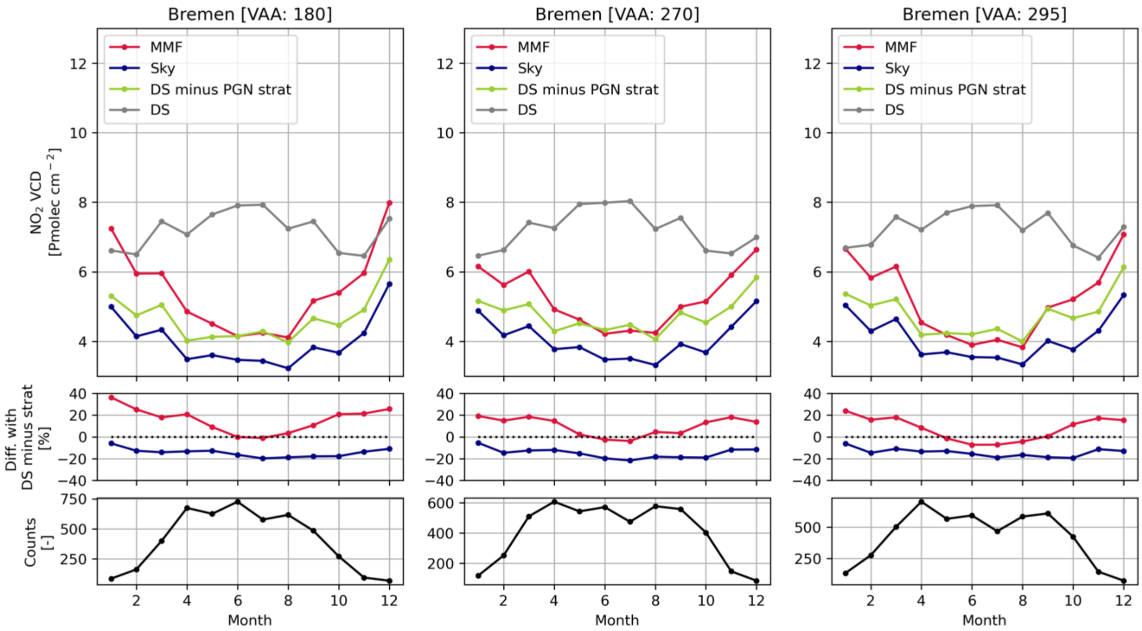

Figure A7. Monthly mean comparison of tropospheric and total NO_2 ground-based observations at Bremen, discriminated by viewing azimuth angle (VAA). The upper panels show MAX-DOAS MMF tropospheric columns (MMF, red), Pandora sky-scan tropospheric columns (Sky, blue), Pandora direct-sun tropospheric columns obtained by subtracting the stratospheric component from the Pandora climatology (DS minus PGN strat, green), and Pandora direct-sun total columns (DS, gray). The middle panels show the relative differences between Pandora direct-sun tropospheric columns (DS minus PGN strat) and MAX-DOAS MMF (red) and Pandora sky-scan (blue) tropospheric measurements. The lower panels show the number of collocated observations for each analyzed station.

12. Line 561, are there any nearby water pixel influences in TROPOMI for Athens and Thessaloniki, where fitted uncertainties are more than twice the expected values.

Response:

For Thessaloniki, TROPOMI pixels containing the coordinates of the ground-based station can include both land and water surfaces, which is likely one of the reasons for the higher uncertainties obtained at this site. In the case of Athens, although the city is located close to the coast, the TROPOMI pixels containing the coordinates of the ground-based station cover only land surfaces. However, the local topography is highly variable, with mountains located to the north, east, and west of the monitoring station, which likely contributes to the higher uncertainties observed there.

To clarify this point and avoid repetition in the manuscript, we have added a short statement in line 607 as follows:

> *"For example, the presence of mountainous terrain surrounding the ground station in Athens, and the combination of land, coastal, and mountainous areas within the satellite footprint in Thessaloniki, may explain the higher uncertainties observed at these sites."*

A more detailed discussion of this aspect was already included in the manuscript, now starting at line 701.

> *"The complex topography surrounding these sites is a likely contributor to the increased uncertainty. Athens is enclosed by mountains to the north (Parnitha, Penteli), east*

(Hymettos), and west (Egaleo), while the Saronic Gulf to the south restricts air-mass dispersion within the basin (Skoulidou et al., 2021; Grivas et al., 2008). Furthermore, the local MAX-DOAS instrument is also installed on one of these surrounding hills, introducing additional representativeness differences relative to the satellite footprint. Thessaloniki combines coastal terrain along the Thermaic Gulf with mountainous influences from Mount Hortiatis, creating pronounced sea–land breezes and valley–mountain circulations that produce strong horizontal gradients and rapidly varying air masses (Skoulidou et al., 2021; Moussiopoulos et al., 2009). Innsbruck is located in the narrow Inn Valley, where steep mountain walls tightly constrain atmospheric flow and favor strong spatial heterogeneity in pollutant distributions. Such complex orography generates concentration gradients at scales smaller than TROPOMI's spatial resolution, and the semi-random pixel location of TROPOMI on each orbit can result in retrievals that alternately emphasize coastal, urban, or mountainous sectors (Thessaloniki, for example)."

13. Figure 16: I recommend adding a figure showing the absolute error as a function of the NO_2 column (from ground-based instruments). This would help demonstrate whether the higher-column underestimation in TROPOMI operational can be explained by the use of the high-resolution CAMS a priori profiles in the retrieval.

Response:
A figure showing the relative error [(TROPOMI–Ground)/Ground]×100% has been added to the appendix as Fig. A13 and is now referenced in the main text.

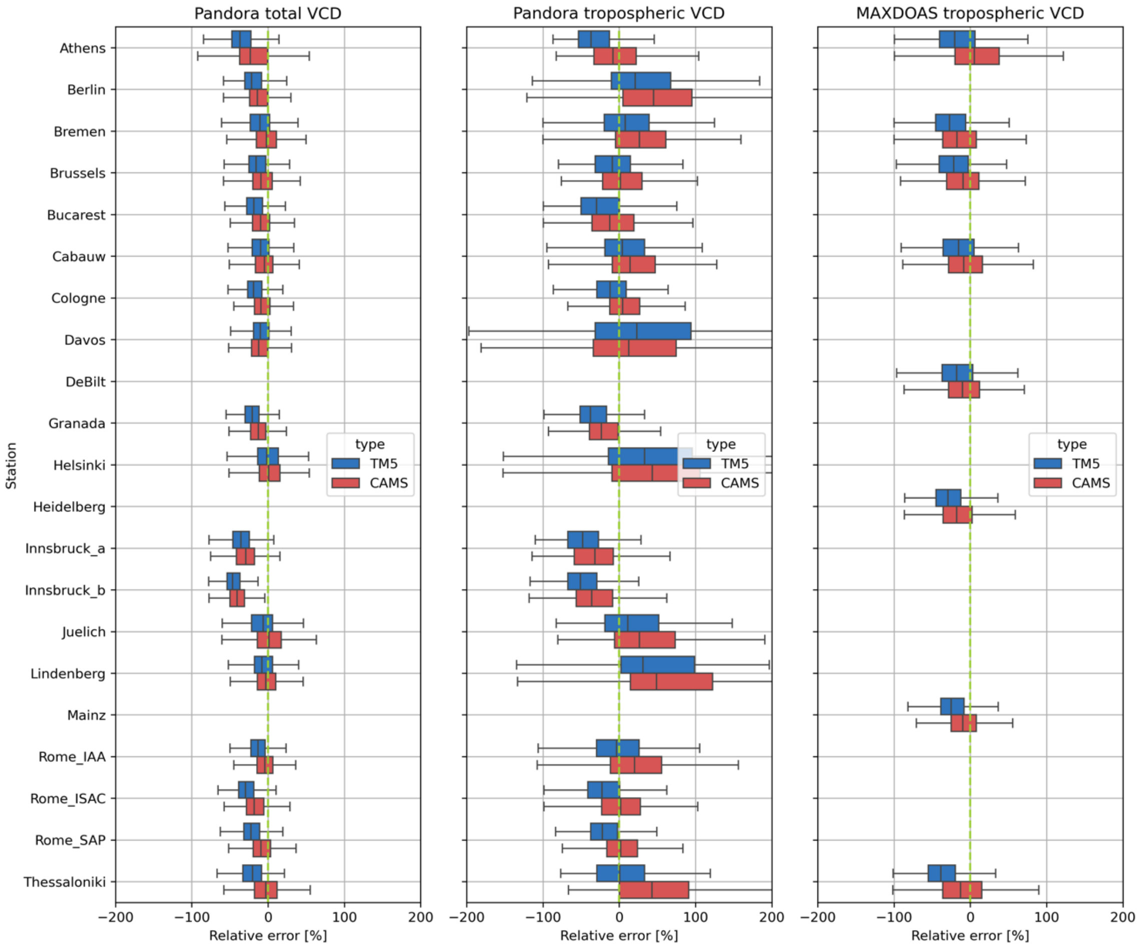

Figure A13. Distributions of the relative differences between TROPOMI and ground-based observations, using TM5-MP (blue) and CAMS (red) a-priori profiles. Results are shown for individual stations (vertical) for the Pandora total column (left), tropospheric column (middle), and MAX-DOAS MMF (right) comparisons.