

Referee #1

This paper presents a cloud retrieval algorithm utilizing a broader O₂-O₂ absorption bands between 435-495 nm, along with correction methods including de-stripping, offset correction for slant column density, and temperature corrections. It also incorporates auxiliary data, such as meteorological data and surface albedo climatology, in the retrievals. The effect of each improvement (except for the wider fitting spectral range) is analyzed using real measurements from TROPOMI and OMI, comparing the results with those from the classic OMCLDO2 algorithm. The TROPOMI and OMI retrievals align better using the proposed algorithm. NO₂ retrievals are also corrected using the proposed cloud results, OMCLDO2 cloud results, and cloud results from the FRESCO algorithm. The corrected NO₂ retrievals are then compared with one another. The theory is sound, and the analysis is thorough. I recommend the paper be accepted after minor revisions.

1. Section 3.3: Does the correction for across-track variability (de-stripping correction) affect the retrievals of cloud fraction? This seems not to be demonstrated in the section.

We have added a sentence in the revised manuscript:

“Additionally, this impact on cloud fraction retrieval is negligible.”

2. Section 3.4 introduces the offset correction for slant column density. However, much of the content describing the temperature correction seems to belong in Section 3.5.3. This overlap may cause confusion for the readers. Additionally, why is an offset of $-0.08 \times 10^{43} \text{ molec}^2 \text{ cm}^{-5}$ applied to the TROPOMI SCDs? This offset appears to be the corrected value intended for this section, but how this value is derived is not explained.

In section 3.4, we removed the sentence “Since the O₂-O₂ SCD retrieval uses an absorption cross-section at a fixed temperature, this factor aligns the retrieved and modeled O₂-O₂ absorption, compensating for the variation of O₂-O₂ absorption due to temperature changes.” As it is repeated in section 3.5.3

Additionally, we have added:

”This offset corresponds to the difference in the mean O₂-O₂ SCD values between OMI and TROPOMI for scenes with cloud fractions between 0 and 0.05 over the two study regions.”

3. Is radiometric cloud fraction the same as effective cloud fraction? The two terms are used interchangeably, but the relationship between them is not clarified in the paper.

Yes, the radiometric cloud fraction and effective cloud fraction refer to the same quantity in this study. To avoid confusion, we have revised the manuscript to use the term effective cloud fraction consistently throughout

4. 545 “We”-> “we”

Corrected.

Referee #2

General comments

The article (Harmonized Cloud Datasets for OMI and TROPOMI Using the O2-O2 477 nm Absorption Band, by Huan Yu et al.) describes an essential (and timely) step that leads to a closer agreement between the retrieved OMI and TROPOMI cloud properties. However, for the derived cloud pressures, the OMI/TROPOMI consistency relies (in my opinion, in a major way) on the TROPOMI slant-column adjustment. Without it, the OMI/TROPOMI differences could be as large as in the already implemented OMCLDO2 retrievals.

Thank you for your comments. This is partially correct when considering the cloud correction applied in the NO2 retrieval, which primarily focus on the polluted regions. Without this offset correction, the agreement using BIRA-IASB cloud corrections becomes more similar to that obtained with OMCLDO2, although it still remains slightly better.

In the revised manuscript, the following table has been included to summarize the impact of the improvements in the BIRA-IASB cloud pressure retrieval compared to the OMCLDO2 approach. The results show that the most significant difference arises from the use of different settings in DOAS fit.

Table 2: Impact of the key improvements in the BIRA-IASB cloud pressure retrieval compared to the OMCLDO2 approach, and the overall differences between the two retrievals. For each improvement, the BIRA-IASB retrieval is applied, and the cloud pressure difference resulting from the individual change is calculated. The analysis is based on one day of OMI (1 October 2004) and TROPOMI (1 October 2018) measurements, restricted to snow/ice-free pixels within the 50°S to 50°N latitude range.

	Cloud fraction ^a >0.2	0.05<Cloud fraction<0.2, Ocean	0.05<Cloud fraction<0.2, Land
O2-O2 SCD fitting ^b	OMI: 28±35hPa TROPOMI: -17±34hPa	OMI: -5±85hPa TROPOMI: -78±84hPa	OMI: -62±103hPa TROPOMI: -188±119hPa
Correction for OMI across-track variability	0±15hPa	1±28hPa	1±38hPa
TROPOMI O2-O2 SCD Offset correction: - 0.08×10 ⁴³ molec ² cm ⁻⁵	-17±6hPa	-31±13hPa	-44±19hPa
Updated temperature correction	-17±5hPa	-25±11hPa	-34±16hPa
Updated surface albedo ^c	5±11hPa	22±34hPa	31±74hPa
Overall difference for OMI	20±36hPa	70±105hPa	26±126hPa
Overall difference for TROPOMI	-32±28hPa	-50±68hPa	-147±98hPa

^a cloud fraction is from the BIRA-IASB retrieval

^b the wavelength dependence due to the use of different fitting windows between the BIRA-IASB and OMCLDO2 retrievals is not accounted for.

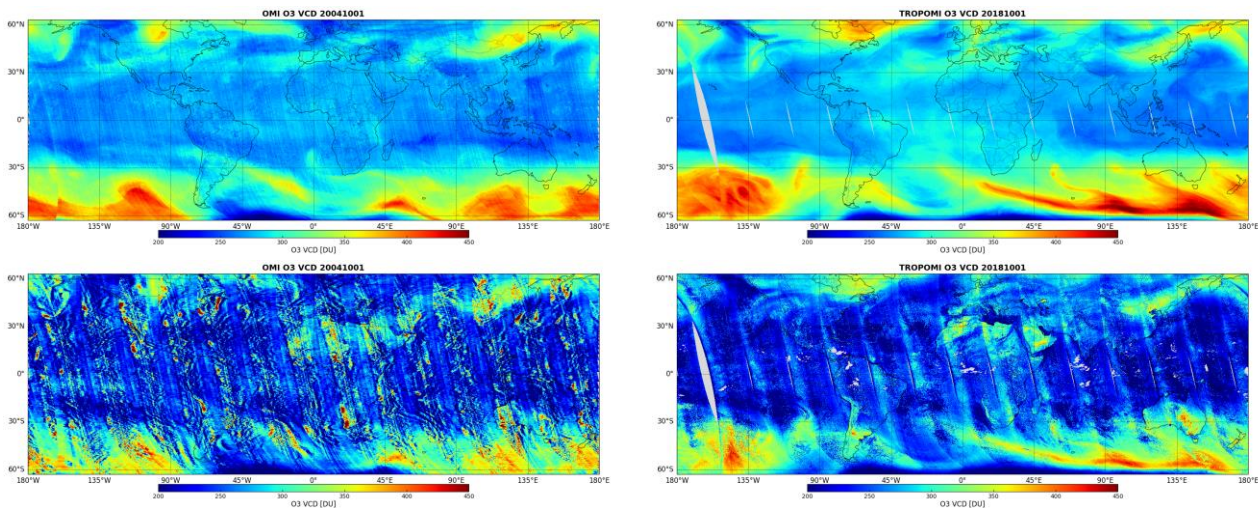
^c comparison between use of OMI mode LER (Kleipool et al., 2008) and TROPOMI DLER (Tilstra et al., 2024)

The Ozone absorption greatly impacts the wavelength range used in the described O₂-O₂ retrievals. As a ‘sanity check’, I may advise comparing the O₃ SCDs retrieved in the proposed approach to the OMI O₃ SCDs (OMDOAO3). If there are any large, systematic (in essence, VZA and SZA-dependent) differences between the two O₃ products, this may imply biases in the retrieved O₂-O₂ SCDs. E.g., one may note the large high-latitude differences between different approaches (Figure 2). Could these be related to the Ozone interference, besides the implied differences in the surface-albedo characterization?

Thanks for the suggestions. Indeed, there is relatively strong interference from the O₃ cross-section in the O₂-O₂ fitting window.

The figure below shows some differences in the O₃ retrieval between the operational products and our DOAS fitting results. However, it should be noted that the O₂-O₂ fitting window is not optimal for O₃ retrieval. Additionally, there is no systematic difference observed between the results from OMI and TROPOMI.

The difference in O₃ slant columns between the BIRA-IASB and OMCLDO2 retrievals can be partly attributed to discrepancies in the O₂-O₂ retrieval (see Figure 2 of the manuscript). In general, large differences in O₃ SCD corresponds to large discrepancies in O₂-O₂ SCD retrieval, except at high latitudes where this relationship weakens. Notably, the correlation behaves differently over desert and ocean regions. Additionally, the O₃ SCD difference between the two retrieval approaches show generally consistent patterns for both OMI and TROPOMI, while the O₂-O₂ SCD differences vary significantly between the two instruments, showing a systematic bias (cf. Figure 2b and 2e),



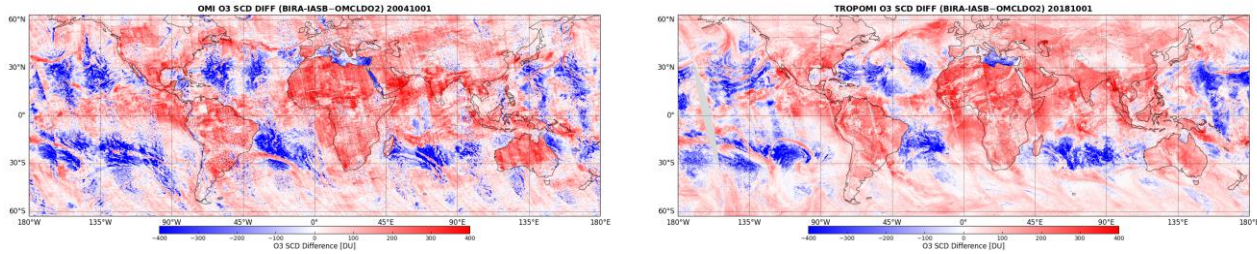


Figure: comparison of O3 retrieval. Top panel: total ozone column from operational products (OMI OMDOAO3 and the operational TROPOMI total ozone product); Middle panel: total ozone column derived from both our DOAS fit and OMCLDO2 for O2–O2 SCD retrieval, obtained by dividing the fitted slant column by the geometric AMF; Bottom panel: differences in O3 SCD retrieved from the O2–O2 fitting window between BIRA-IASB and OMCLDO2. The left column presents results for OMI, while the right column shows results for TROPOMI.

Specific comments

Abstract:

“Due to the suboptimal quality of solar irradiance measurements by OMI...” Consider changing this to: “Due to the inadequate signal-to-noise ratios in the daily solar irradiance measurements by OMI...”. ‘Suboptimal’ may sound like a polite ‘inferior’.

Thank you for the suggestion, and corrected.

“Notably, our approach demonstrates improved consistency in cloud parameters, especially cloud pressure, between the two sensors compared to OMCLDO2.” This comes in contradiction with the statement from Section 4.1.2 that compares the cross-track trends (thus the offsets) between the BIRA-IASB and OMCLDO2 approaches, where line 503 states “This analysis does not allow us to determine which algorithm achieves better agreement between the two sensors.” Indeed, the metrics are many, and many of them show mixed performances. As presented, it mostly relies on the systematic -0.08×10^{43} molec² cm⁵ TROPOMI SCD offset. This should be explicitly mentioned in the Abstract and the main text.

Due to the significant differences in spatial resolution between TROPOMI and OMI, relatively more cloud free measurements are available from TROPOMI. Additionally, statistical analysis shows that cloud pressure retrieval for low cloud fraction cases exhibit noticeably different behavior compared to those for cloudy scenes. As a result, even with consistent cloud retrieval algorithm, the averaged cloud pressure values may have slightly differences between OMI and TROPOMI measurements due to the different pixel size.

In the revised manuscript, we have updated this figure and included the average cloud pressures for both cloudy and low cloud fraction cases to address this issue. Accordingly, the statement on line 503 has been removed, as it is no longer relevant.

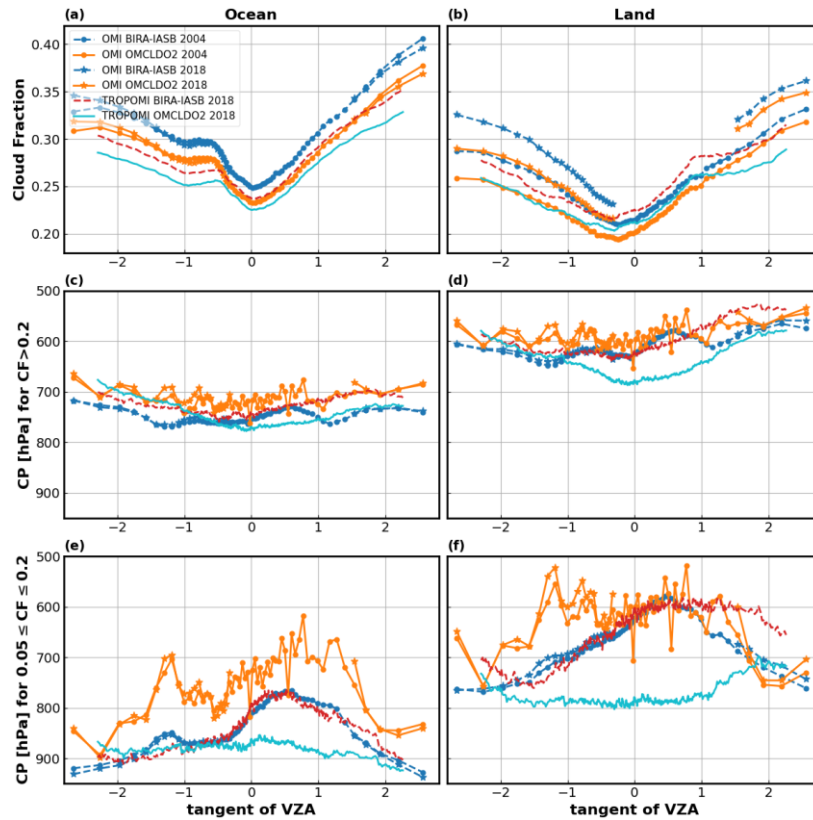


Figure 14: Across-track dependence of monthly mean cloud retrievals from OMI and TROPOMI for October, based on the measurements between 50°S and 50°N latitudes. The left panels present results over ocean, while the right panels show results over land. The analysis includes cloud fraction (top), cloud pressure in cloudy scenes (middle), and cloud pressure in low cloud fraction scenes (bottom). The legend details the sensors, retrieval methods, and time periods included in the analysis.

In addition, we have included this value in both abstract and conclusion:

“an offset correction of $-0.08 \times 10^{43} \text{ molec}^2 \text{ cm}^{-5}$, motivated by radiative transfer simulations, is applied in the TROPOMI retrieval to improve the consistency with OMI.”

“A SCD offset of $-0.08 \times 10^{43} \text{ molec}^2 \text{ cm}^{-5}$ is applied in the TROPOMIS retrieval to improve consistency with OMI measurements.”

“... primarily attributed to differences in L1b data.” Consider expanding this to “...primarily attributed to differences in L1b data that show systematic biases between the OMI and TROPOMI reflectances”.

Corrected.

Table 1. Consider expanding/amending the comments

1. “ I0 correction is applied with SCD of $5 \cdot 10^{15} \text{ molec./cm}^2$ ” Does this mean: an offset of $5 \cdot 10^{15} \text{ molec./cm}^2$

is applied to the cross-sections? Or something else?

Following Eq. A3 in Aliwell et al., 2002, the I_0 -corrected absorption cross section is given by:

$$\sigma_{corrected}(\lambda') = \frac{1}{X} \ln \left\{ \frac{\int I_0(\lambda) \cdot \exp[-\sigma(\lambda) \cdot X] \cdot W(\lambda - \lambda') d\lambda}{\int I_0(\lambda) \cdot W(\lambda - \lambda') d\lambda} \right\}$$

Here, I_0 represents the solar Fraunhofer spectrum, $W(\lambda)$ is the normalized instrument slit function, $\sigma(\lambda)$ denotes the absorption cross section and X is the corresponding column amount of absorber. The correction shows a weak dependence on X , due to nonlinearity in the integral term. In practice, a representative high measured value of X is typically used. In our analysis, modifying the NO₂ SCD between $5 \cdot 10^{15}$ and $2 \cdot 10^{16}$ has negligible impact on O₂-O₂ slant column retrieval.

The footnote is modified by: “ I_0 correction is applied based on a NO₂ SCD of $5 \cdot 10^{15}$ molec./cm² using Eq. A3 from Aliwell et al., 2002”.

2. same as for a)

The footnote is modified by: “ I_0 correction is applied based on a O₃ SCD of $2 \cdot 10^{19}$ molec./cm² using Eq. A3 from Aliwell et al., 2002”.

3. “additional cross-section taken as the inverse of the reference spectrum.” It is not clear how this could be applied to the wavelength shifts.

It’s an error, this footnote(d) actually refer to the intensity offset correction, and corrected it.

For the offset correction, we use the equation

$$\log(I(\lambda)) = \log(I_0(\lambda)) - \sum \sigma_i \cdot c_i + \frac{\text{offset}(\lambda)}{I_0(\lambda)}$$

instead of

$$\log(I(\lambda)) = \log(I_0(\lambda)) - \sum \sigma_i \cdot c_i + \frac{\text{offset}(\lambda)}{I(\lambda)}$$

Although the difference in results between the two approaches is minimal, using $I_0(\lambda)$ significantly improves performance, especially when nonlinear term such as wavelength shift are included in the fit.

Table 1. Also, mention the intensity offset, if applicable (e.g., line 183).

We have added:

Intensity offset: first-order offset (additional cross-section taken as the inverse of the reference spectrum (see Eq. 5.6 in (Danckaert et al., 2017))

I.167 Please comment on how the broader fitting window helps to improve the low-SCD retrievals.

When we extended the fitting window from 460–490 nm to 435–495 nm while keeping all other settings unchanged, the occurrence of negative SCD retrievals was reduced. On the other hand, increasing the polynomial order within the 460–490 nm window also led to increased retrieved O₂–O₂ SCDs, although this may indicate overfitting. Therefore, we have removed this statement, as we are not confident that it represents a genuine improvement.

The main advantage of the broader fitting window is its improved handling of broadband surface reflectance effects, as the current settings is less sensitivity to the polynomial order compared to the DOAS fit using the 460–490 nm window.

Figure 2. Were the shown BIRA-IASB OMI retrievals de-striped? For better consistency (clarity of the trends), they should not be. Please clarify. Please also comment on the x-track features seen in the BIRA-IASB-OMCLDO2 differences (panel b). Are the shown (panel d) TROPOMI SCDs adjusted by $-0.08 \times 10^{43} \text{ molec}^2 \text{ cm}^{D5}$? If they are not, then in this particular example I would insist on applying such an adjustment prior to comparison.

In this comparison, the BIRA-IASB retrievals from both OMI and TROPOMI are presented without any post-processing or corrections applied; thus, the results directly reflect the differences from the DOAS fitting itself. As shown in Table 2 above, the largest discrepancy between our retrieval and OMCLDO2 comes from the DOAS fitting, whereas the effects of de-striping and offset correction are relatively small. The current structure of the manuscript, which examines each correction separately, effectively emphasizes their individual impacts. Combining all corrections would obscure their distinct contributions, so we recommend retaining the existing approach.

For x-track features, we have included:

“The across-track dependence visible in the OMI difference map is likely caused by calibration issues in the OMI L1b data, which introduce across-track variability in trace gas retrievals (Boersma et al., 2007) and this effect varies depending on the retrieval approach used. A correction methodology for this effect will be detailed in the following section.”

How typical are the differences shown in Figure 2? Are these season-dependent? Please comment on.

The differences shown in Figure 2 are highly representative, exhibiting no significant seasonal dependence. Our analysis uses at least one full year of OMI and TROPOMI data, ensuring comprehensive seasonal coverage. Due to space constraints, this seasonal-dependence is mentioned in Section 4.3, which confirms the seasonal stability of our results.

I.221 “Use the median SCDs from rows 2–21 in the desired year, subtracting the mean of the corresponding values...” What are these median SCDs? Are these SCDs adjusted for the linear fits? Are the medians derived row-by-row? What are these corresponding values: the median(s) or something else? The description must be expanded, keeping

in mind that at some point it could be implemented by somebody else.

The median values are from step 1, and derived row-by-row, without any adjustment.

We have rephrased this paragraph:

“Collect the median SCDs obtained from step 1 for rows 2 to 21, calculate their average, and then compare this value with the mean of similarly calculated values from the same period during the reference years (2004–2007) to determine an offset, which reflects the interannual variation of O₂–O₂ SCD”

I may suggest normalizing (beforehand) all SCDs by $\tan(\text{VZA})$ and, possibly (?), by $\cos(\text{SZA})$; or, alternatively, by the geometric air mass factor. This could further simplify the approach.

Thank you for the suggestion. However, none of these approaches are effective. Please note that box-AMF at low atmospheric layer shows very weak dependence on solar/viewing geometry, whereas the box-AMF values are close to geometric air mass factor at higher altitudes. The O₂-O₂ SCDs depend on the combination of these two effects. Although we observe a clear correlation between O₂-O₂ SCD and $\tan(\text{VZA})$, this relationship cannot be quantified by simple geometric parameterizations.

1.227 “The data selection method used in Figure 3(a) avoids regions with significant variations in surface albedo and surface pressure.” The described destriping approach uses SCDs, and SCDs only. If SCDs are additionally filtered for these two factors, please add a comment. Otherwise, I’m not able to follow the statement – please explain.

We have rephrased the sentence:

“The data selection method used in Figure 3(a) excludes land regions due to the significant variations in surface albedo and surface pressure, as these factors strongly affect the O₂-O₂ SCD.”

1.237 Even with the minimal inter-annual variability of the striping patterns, there is no guarantee that these patterns remain stable intra-annually. Please either comment on or provide additional (Appendix) evidence of the short-term (seasonal) stability.

The striping patterns are generally stable, with small seasonal variation as well. However, we consider inter-annual variability to be more critical here, especially since smoothed reference is not available after 2007. If strong inter-annual variability is present, this approach would not be feasible. In contrast, substantial seasonal variation would have no impact on the methodology.

Figure 4. It is impossible to assess the impact of de-striping from 2D plots. Please add 1 panel that shows the average (say, for scanlines 1150-1200) cloud pressures for the three products (b-d).

Thank you for the suggestion. It is challenging to illustrate the impact of the de-striping correction using averages from such a limited dataset. Moreover, the correction is highly dependent on the cloud fraction, an effect that is not apparent in the average data. Instead, we have revised Figure 4(d) to directly show the differences in cloud pressure

with and without the de-stripping correction. This revised panel clearly highlights the row-dependent of the correction. The resulting differences in cloud pressure are generally within ± 30 hPa, with significantly larger deviations observed when the cloud fraction approaches zero. The OMCLDO2 cloud pressure map has been removed, as its across-track dependence is already addressed in Section 4.1.2.

We have rephrased the sentence in the revised manuscript:

“As shown in Figure4(d), the differences in cloud pressure due to this correction are generally within ± 30 hPa, with significantly larger deviations observed when the cloud fraction approaches zero.”

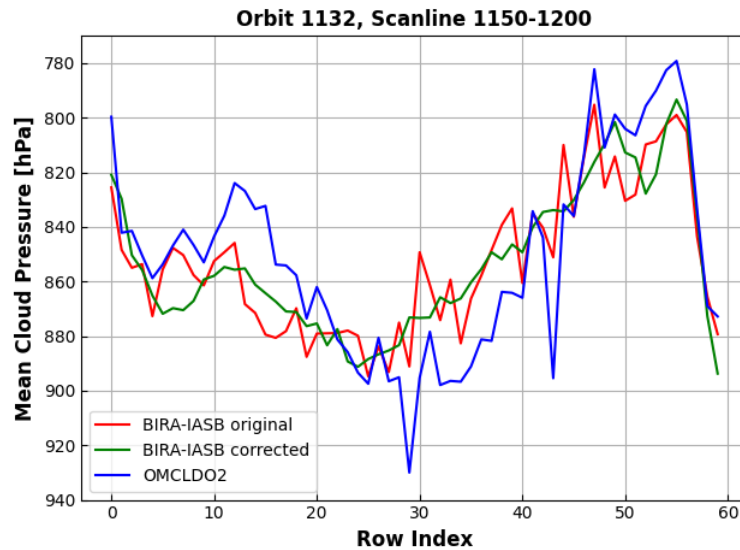


Figure: Row dependence of averaged cloud pressures from the OMI swath (scanlines 1150–1200) for orbit 1132 on 1 October 2004.

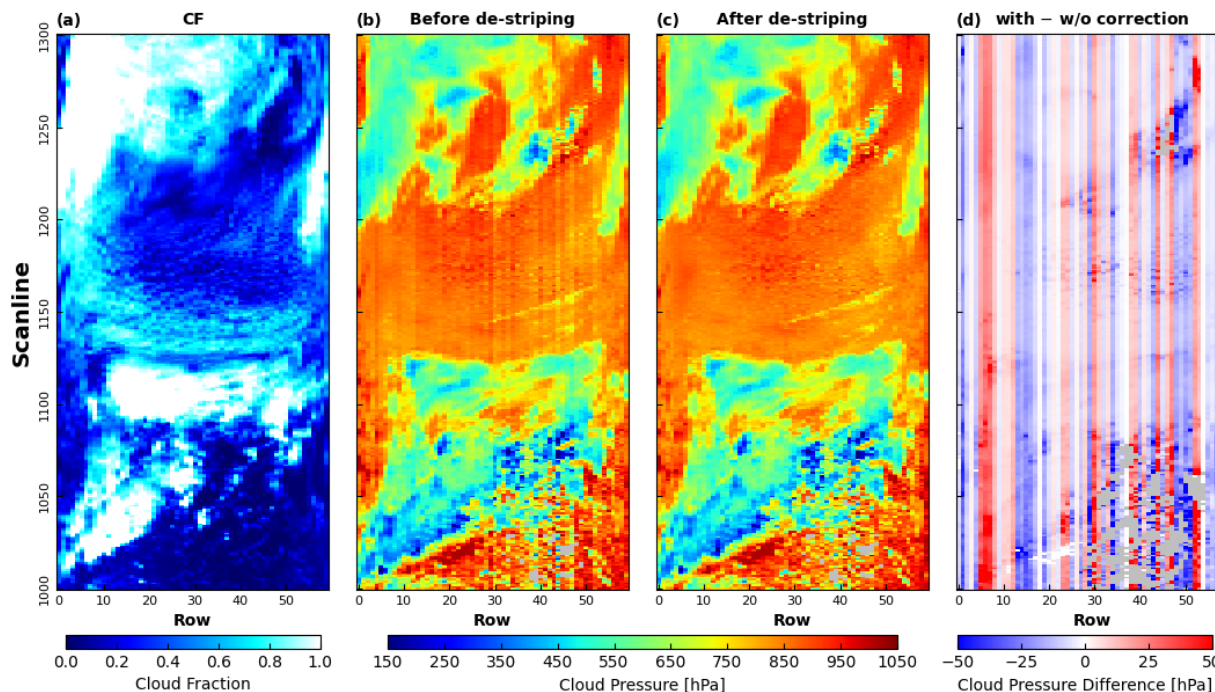


Figure 4: OMI O2-O2 cloud retrievals for BIRA-IASB cloud fraction (a), BIRA-IASB cloud pressure before (b) and after (c) de-stripping correction, and (d) difference between with and without correction. The data shown represent a segment of an OMI swath (scanlines 1000-1300) from orbit 1132 on 1 October 2004. Pixels with cloud fractions below 0.05 have been removed from the cloud pressure maps.

1.280 Is/are there any reason(s) why OMI is considered the ‘truth’, thus prompting the TROPOMI adjustment? Considering that TROPOMI retrievals use more advanced surface characterization, one may side with TROPOMI as a ‘truth’. Please comment on.

The purpose of this simulation study is to verify that the O2-O2 SCD ratio approaches 1 as the cloud fraction approaches 0. Accordingly, a correction is applied to the TROPOMI data in this case—though this may be coincidental. Any changes in the DOAS retrieval or the simulation settings could lead to different correction results. Given the current configuration, we apply this correction to the TROPOMI data.

1.300 “...this study uses the TOA reflectance, which accounts for both Rayleigh scattering and atmospheric absorption...” Ozone is an important contributing factor, especially at high VZA and SZA angles. Is it accounted for? Please mention what atmospheric absorptions are taken into account.

Yes, both NO2 and O3 absorptions are included. We have added it:

“...which accounts for both Rayleigh scattering and absorptions by O3 and NO2...”

1.319 "...where the cloud fraction lies within [0, 1.5]..." What necessitates the range extension to (completely unphysical) 1.5 – please explain.

Since our retrieval assumes a fixed cloud albedo of 0.8, a higher actual cloud albedo can result in retrieved cloud fractions exceeding 1. In real measurements, the retrieved cloud fraction values can exceed 1.5 in cases with high surface albedo and large SZAs. For cases with cloud fraction larger than 1, the current retrieval approach becomes unreliable.

1.345 "Here, T represents the atmospheric temperature representative of satellite observations..." The key word is 'representative'. Considering the multitude of contributing factors, please provide more details on choice of the representative temperature. Is this $c(T)$ related to $C(T(p))$ from eq. 7? If true, then change eq. 6 to $c(T(p)) = \dots(T(p) - T_0)$... Otherwise, explain how $c(T(p))$ and $c(T)$ are brought together.

Yes, corrected it.

1.355 "...the temperature correction for the O2-O2 cross-section must be accounted for when creating the inverted LUT." Please provide more details on how this is done. Via an additional LUT dimension?

We have rephrased the sentence:

"the temperature correction for the O2-O2 cross-section must be accounted for in the calculation of O2–O2 VCD (see Eq. 4 and 5) when creating the inverted LUT"

Figure 7 "...compares temperature correction factors calculated using the BIRA-IASB and OMCLDO2 algorithms..." Note that the only unbiased way to assess the changes caused by the different temperature corrections is to use these two corrections within the framework of the same retrieval algorithm. Otherwise, other contributing factors (LUTs and the adopted interpolation approach, surface characterization, general DOAS setup, etc., etc.) may not be cleanly disentangled from the temperature impact. Consider either performing such a test or removing Figure 7(b) and the related discussion.

Yes, this study is based on the BIRA-IASB retrieval approach, but it employs the temperature correction factors derived using different ways. We have added the text in Figure 7 (b):

"Both cloud retrievals implement the BIRA-IASB approach, with temperature correction factor being the only parameter calculated separately using both the BIRA-IASB and OMCLDO2 methods."

1.422 "Additionally, cloud pressure retrievals are shown only for pixels with cloud fractions above 0.01." Later, in the caption of Figure 15, the authors say: "To ensure reliable cloud pressure comparisons, pixels with a cloud fraction below 0.05 are excluded, as very low cloud fractions lead to high uncertainties in cloud pressure retrievals." Agreed! Please make sure that this 0.05 threshold is consistently implemented in the revised text (e.g., in Figures 10, 13, 14 and elsewhere).

Corrected, and corresponding figures are updated.

Section 4.1.1 If the adjustment ($-0.08 \times 10^{43} \text{ molec}^2 \text{ cm}^{-5}$) was applied to the TROPOMI data, mention this early in the Section.

This adjustment has been mentioned in Table 2.

Sect. 4.1.1, Figures 11-14. It would be very helpful to provide a table with the relevant characteristics (offset, slope, correlation) for all the performed comparisons, cloud fractions first, followed by the cloud pressures. The discussion could be shortened and streamlined hereafter.

We have added Table 2 shown above, summarizing the impact of the main improvements in the BIRA-IASB cloud pressure retrieval compared to the OMCLDO2 approach, and included the following paragraph in section 4.1.1:

“Table 2 summarizes the impact of each improvement in our cloud pressure retrieval relative to OMCLDO2, as well as the overall differences between the two retrieval approaches, based on one day of OMI and TROPOMI data. Effects on cloud fraction are not included, as the implemented changes have minimal influence in this regard. The impact is generally much greater in scenes with low cloud fraction than in cloudy conditions, and it tends to be more pronounced over land than over ocean. The results suggest that the most significant discrepancies primarily arise from differences in the DOAS fitting settings. While the wavelength dependence introduced by using different fitting windows in the O2-O2 SCD retrievals is not accounted for in this analysis, its impact is expected to be minor.” (mostly 1-2% between the AMF calculated at 465 and 475nm)

Figure 13. There are extremely large (300-400 hPa) offsets in the shown TROPOMI low-cloud-fraction retrievals, both over land and oceans. The introduced SCD offset may account for a very small fraction (~50 hPa) of these differences. Where does this (very concerning!) BIRA-IASB and OMCLDO2 difference come from?

As shown in Table 2 and Figure 2, the most significant difference in cloud pressure retrieval is due to the O2-O2 SCD difference between BIRA-IASB and OMCLDO2, especially for low cloud fraction cases, with an average discrepancy of approximately $0.5 \times 10^{43} \text{ molec}^2 \text{ cm}^{-5}$, corresponding to 15–20% of the total O2-O2 SCD. This difference is much larger than the applied offset correction values.

It should also be noted that variations in O2-O2 slant column density (SCD) have a more significant impact on high cloud retrieval than on low cloud retrieval.

Figure 14. The sharp increase of cloud fractions toward the edges of the swaths is puzzling, especially considering the absence of such prominent trends in the OMI retrievals based on an alternative approach (Vasilkov et al. 2018). This also applies to the west-east cloud-pressure differences seen in the discussed retrievals. I hope these subjects will be followed upon by the authors.

Our results are very similar to other TROPOMI cloud retrieval results (see Figure 16 and 17 in Latsch et al., 2022). The average cloud fraction ranges from 0.2 to 0.4, with the lowest values typically near nadir and slightly increasing with VZA, which is consistent with the patterns reported by Latsch's findings. In contrast, Vasilkov et al., 2018

present across-track cloud fraction patterns based on scenes with low cloud fractions (between 0.05 and 0.25), which may account for the differences observed.

1.603 Please remind the reader that the OMCLDO2 OMI/TROPOMI retrievals use [very!] different surface albedo datasets. The differences could be mostly related to this aspect.

As shown in Figure A1, the difference in surface albedo between the OMI and TROPOMI albedo climatology datasets is generally small, typically around 0.01–0.02, with slightly large difference over desert and snow/ice-covered regions. The OMI albedo values tend to be biased higher. This result has only a minor impact on cloud fraction retrievals (see Table 2 and Figure 12). We believe that the effect of L1b differences between OMI and TROPOMI is likely much larger than the impact of using different surface albedo datasets in the cloud retrieval. (See Figure 19a/19c and Figure 20).

Technical comments

1.122 Mention that Band 4 is used for the O₂-O₂ retrievals. Also mention how the saturation flags are accounted for in the retrievals.c

We have added:

“This saturation can affect the O₂-O₂ cloud retrieval, which rely on measurements from Band 4. To mitigate this, spectral pixels flagged as saturated are excluded from data analysis.”

1.193 “In contrast, for OMI, the limited quality of the daily solar measurements...” – consider adding ‘daily’.

Corrected.

Figure 5, the caption: “Data are binned by cloud fraction intervals of 0.1...” – use 0.1 instead of 0.01

This should be 0.01, as the comparison focuses exclusively on nearly cloud-free scenes (The x-axis in Figure 5 ranges from 0 to 0.1).

Figure 6(a) – Please check the match between the color legend and the plotted curves.

Corrected.

1.478 “The retrieved cloud fraction is constrained between 0.05 and 1...”

Cloud fraction retrievals are clipped to the [0, 1] range; however, for the cloud pressure analysis, only pixels with cloud fraction greater than 0.05 are used.

Reference:

Boersma, K. F., Eskes, H. J., Veefkind, J. P., Brinksma, E. J., Van Der A, R. J., Sneep, M., Van Den Oord, G. H. J., Levelt, P. F., Stammes, P., Gleason, J. F., and Bucsele, E. J.: Near-real time retrieval of tropospheric NO₂ from

OMI, Atmos. Chem. Phys., 7, <https://doi.org/10.5194/acp-7-2103-2007>, 2007.

Danckaert, T., Fayt, C., Van Roozendael, M., De Smedt, I., Letocart, V., Merlaud, A., and Pinardi, G.: QDOAS Software User Manual, Version 3.2, 2017.

Latsch, M., Richter, A., Eskes, H., Sneep, M., Wang, P., Veefkind, P., Lutz, R., Loyola, D., Argyrouli, A., Valks, P., Wagner, T., Sihler, H., Van Roozendael, M., Theys, N., Yu, H., Siddans, R., and Burrows, J. P.: Intercomparison of Sentinel-5P TROPOMI cloud products for tropospheric trace gas retrievals, Atmos. Meas. Tech., 15, <https://doi.org/10.5194/amt-15-6257-2022>, 2022.

Vasilkov, A., Yang, E. S., Marchenko, S., Qin, W., Lamsal, L., Joiner, J., Krotkov, N., Haffner, D., Bhartia, P. K., and Spurr, R.: A cloud algorithm based on the O₂-O₂ 477 nm absorption band featuring an advanced spectral fitting method and the use of surface geometry-dependent Lambertian-equivalent reflectivity, Atmos. Meas. Tech., 11, <https://doi.org/10.5194/amt-11-4093-2018>, 2018.

Referee #3

In this manuscript, the authors report on an improved version of the O₂-O₂ cloud retrieval for OMI and TROPOMI, aiming at consistent trace gas retrievals for the two instruments. The main improvements of the algorithm are the use of consistent a priori data, a larger O₄ fitting window, treatment of the temperature dependence of the O₄ cross-sections, destriping for OMI and an offset correction of the TROPOMI O₄ columns. With these updates, the cloud retrieval results in more consistent cloud parameters between the two instruments than with the current implementations of the O₂-O₂ retrieval, in particular with respect to cloud pressure. Application to tropospheric NO₂ columns also shows good consistency between the two instruments.

The manuscript reports on an interesting study, which fits well into the scope of AMT. It is well written, has a good level of detail and is of relevance for the UV/vis satellite community. I, therefore, recommend it for publication after revisions.

General comments

Although I overall liked the paper and enjoyed reading it, there are several important aspects which in my opinion need to be addressed before publication.

1) Many aspects of the O₄ retrieval have been changed, and it is not entirely clear, which one is the driver of the better agreement between the two instruments that the authors find. The use of the larger fitting window is not really motivated in the manuscript, the temperature correction is physical but was not used on either of the instruments in the past, so the main differences are the use of consistent a priori information and the (not very satisfying) ad hoc offset correction. I suggest that the effect of the different changes is tested separately on a subset of data to clarify this point.

Thank you for your suggestion.

In the revised manuscript, we have added a table summarizing the impact of the main improvements in the BIRA-IASB cloud pressure retrieval compared to the OMCLDO₂ approach.

We have added the following paragraph in section 4.1.1:

“Table 2 summarizes the impact of each improvement in our cloud pressure retrieval relative to OMCLDO2, as well as the overall differences between the two retrieval approaches, based on one day of OMI and TROPOMI data. Effects on cloud fraction are not included, as the implemented changes have minimal influence in this regard. The impact is generally much greater in scenes with low cloud fraction than in cloudy conditions, and it tends to be more pronounced over land than over ocean. Although this analysis does not account for the wavelength dependence introduced by using different fitting windows in the O2-O2 SCD retrieval, the impact of this effect is relatively minor.” (1-2% in the AMF calculated at 465 and 475nm)

Table 2: Impact of the key improvements in the BIRA-IASB cloud pressure retrieval compared to the OMCLDO2 approach, and the overall differences between the two retrievals. For each improvement, the BIRA-IASB retrieval is applied, and the cloud pressure difference resulting from the individual change is calculated. The analysis is based on one day of OMI (1 October 2004) and TROPOMI (1 October 2018) measurements, restricted to snow/ice-free pixels within the 50°S to 50°N latitude range.

	Cloud fraction ^a >0.2	0.05<Cloud fraction<0.2, Ocean	0.05<Cloud fraction<0.2, Land
O2-O2 SCD fitting ^b	OMI: 28±35hPa TROPOMI: -17±34hPa	OMI: -5±85hPa TROPOMI: -78±84hPa	OMI: -62±103hPa TROPOMI: -188±119hPa
Correction for OMI across-track variability	0±15hPa	1±28hPa	1±38hPa
TROPOMI O2-O2 SCD Offset correction: - 0.08×10 ⁴³ molec ² cm ⁻⁵	-17±6hPa	-31±13hPa	-44±19hPa
Updated temperature correction	-17±5hPa	-25±11hPa	-34±16hPa
Updated surface albedo ^c	5±11hPa	22±34hPa	31±74hPa
Overall difference for OMI	20±36hPa	70±105hPa	26±126hPa
Overall difference for TROPOMI	-32±28hPa	-50±68hPa	-147±98hPa

^a cloud fraction is from the BIRA-IASB retrieval

^b the wavelength dependence due to the use of different fitting windows between the BIRA-IASB and OMCLDO2 retrievals is not accounted for.

^c comparison between use of OMI mode LER (Kleipool et al., 2008) and TROPOMI DLER (Tilstra et al., 2024)

2) A significant effort was taken to correct the row dependence of the OMI O4 columns, and the results are certainly an improvement. However, in the final products (Fig. 14), the row dependency of the cloud pressure is smoother but not really smaller than in the original OMI product. It also is different between OMI and TROPOMI. This is a concern as it points at systematic problems in the retrieval. Please discuss this result in more detail.

The average cloud pressure values in the figure contained an inconsistency, as the OMI BIRA-IASB values were calculated over all measurements, whereas the other cloud pressures were computed only for pixels with a cloud

fraction greater than 0.05. We updated this figure using a consistent calculation method for all retrievals, and further separated the average cloud pressure values for both cloudy and low cloud fraction scenes, due to the notably different row dependence observed between these two scene types.

We have updated the paragraph in the revised manuscript:

“The mean cloud pressure values are generally higher over ocean compared to land. For cloudy scenes (cloud fraction > 0.2), OMI retrievals show a weak dependence on VZA for OMI, while TROPOMI retrieves slightly higher cloud pressures near nadir, with values increasing toward the edges of the swath. The mean cloud pressure values from two TROPOMI products are closely aligned on the west side of the swath, whereas on the east side of the swath, the BIRA-IASB cloud pressures are generally higher than those from OMCLDO2. However, no clear west-to-east trend is observed between the two OMI retrievals.

For scenes with low cloud fraction, cloud pressure retrievals exhibit significantly stronger across-track variation compared to cloudy scenes. In such cases, the OMI BIRA-IASB cloud pressure values are generally higher than those from OMCLDO2, while for TROPOMI, BIRA-IASB values tend to be lower. Most cloud pressure retrievals exhibit a consistent broadly across-track pattern, typically with lower values near nadir that decrease toward the edges of the swath. An exception is noted for the TROPOMI OMCLDO2 retrieval over land, where cloud pressures at nadir are slightly higher than those at the swath edges. Over ocean, the OMI and TROPOMI BIRA-IASB retrievals exhibit a consistent across-track behavior. Over land, however, discrepancies arise near the swath edges, likely caused by surface reflectance anisotropy effects resulting from slight differences in solar and viewing geometries between OMI and TROPOMI. Additionally, OMI OMCLDO2 cloud pressures exhibit pronounced across-track variability due to the lack of a de-stripping correction, resulting in amplitudes exceeding 100 hPa in certain detector rows. The difference between the retrievals from 2004 and 2018 is minimal, indicating temporal stability in these features.”

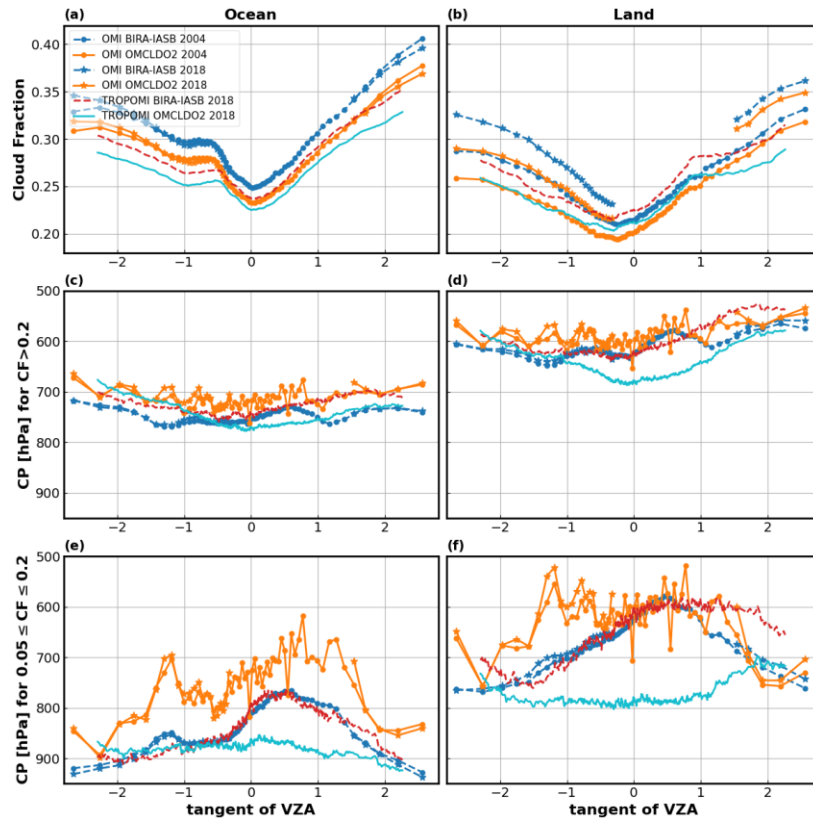


Figure 14: Across-track dependence of monthly mean cloud retrievals from OMI and TROPOMI for October, based on the measurements between 50°S and 50°N latitudes. The left panels present results over ocean, while the right panels show results over land. The analysis includes cloud fraction (top), cloud pressure in cloudy scenes (middle), and cloud pressure in low cloud fraction scenes (bottom). The legend details the sensors, retrieval methods, and time periods included in the analysis.

3) While the results of the improved algorithm are compared in detail with those of the existing O2-O2 algorithm, the real alternative to the new algorithm is the existing FRESKO cloud algorithm. In contrast to the O2-O2 data stored in TROPOMI NO2 files, the FRESKO results are used by the current TROPOMI NO2 and HCHO retrievals, and this is what the new algorithm should (also) be compared to! I think that all comparisons dealing with cloud fractions and cloud pressures need to include the currently used TROPOMI cloud algorithm.

Thank you for the comment. This analysis was conducted but is not included in the manuscript. We compared the two TROPOMI O2-O2 products not only with FRESKO but also with OCRA/ROCINN, the operational cloud product used for cloud correction in the TROPOMI HCHO and SO2 retrievals. While these comparisons are relevant, including them in detail would significantly lengthen the manuscript and potentially divert focus from our primary research objectives.

For the NO2 comparison presented in the manuscript, we included the FRESKO cloud correction, as it is used in the operational TROPOMI NO2 retrieval. From this perspective, we have included a brief discussion comparing our TROPOMI O2-O2 retrieval with the cloud product used in the operational NO2 retrieval.

In the revised manuscript, we have added a paragraph in section 4.2 and included two figures in appendix to compare the pixel-by-pixel difference of cloud fraction and cloud pressure:

“As shown in Fig. A4, the 440 nm cloud fractions agree well with the results from our O2-O2 retrieval. In contrast, the cloud fractions derived from the O2-O2 (477nm) and O2-A band measurements exhibit larger discrepancies, and these differences are particularly evident for low cloud fractions, with differences more pronounced over land. For cloudy scenes, there is generally good agreement in cloud pressure retrieval between our O2-O2 results and FRESKO (Figure A5). However, in scenes with low cloud fractions, the figures show substantial scatter. FRESKO tends to retrieve relatively lower cloud pressure for high cloud cases over ocean, and slightly higher over land.”

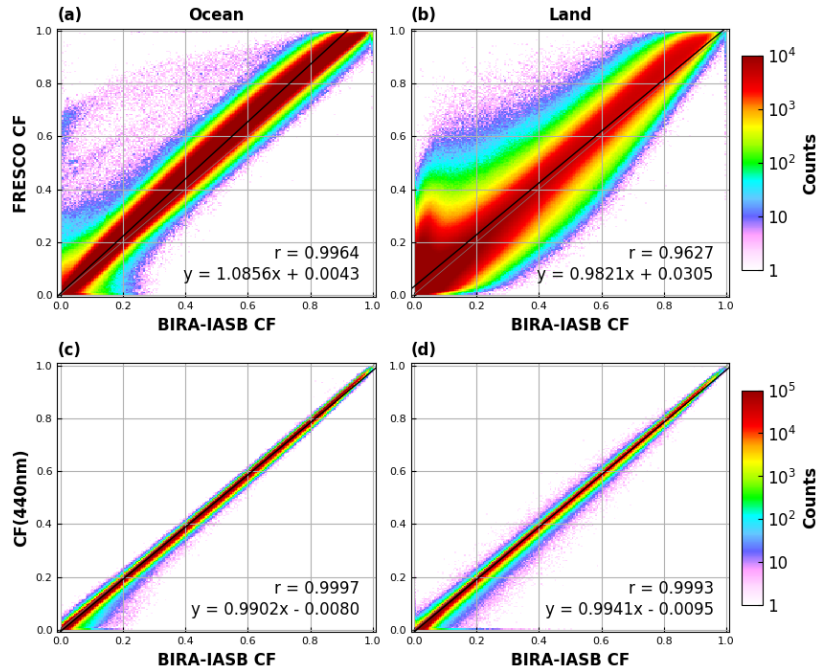


Figure A5: Similar to Figure 12, but showing a comparison between our TROPOMI O2–O2 cloud fraction retrievals and FRESKO (top panel), as well as the 440 nm cloud fraction (bottom panel) used in the operational TROPOMI NO2 retrieval.

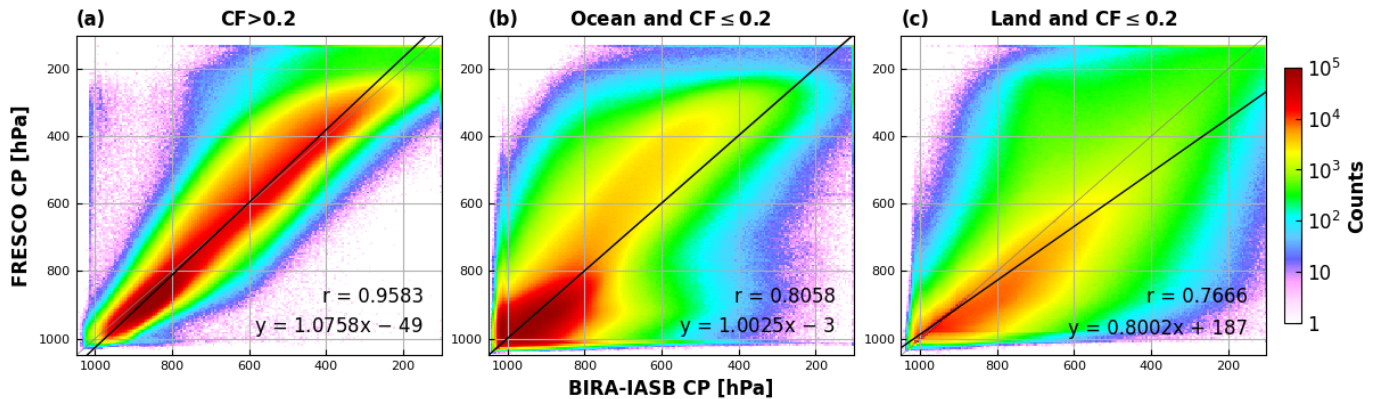


Figure A6: Similar as Figure 13, but for comparison of TROPOMI cloud pressure retrievals between BIRA-IASB

4) I'm not comfortable with the discussion of the effect of using different cloud products on the NO₂ tropospheric columns. On the one hand, the way the numbers are discussed in the text focuses on the largest differences, which are driven by the TROPOMI O₂-O₂ algorithm which has to my knowledge never been used for tropospheric NO₂ retrievals. In that sense, the importance is exaggerated, and in my opinion, differences of a few percent are small considering all the other uncertainties in the retrievals. A more appropriate message would therefore be "cloud correction does not make a big difference for NO₂ tropospheric retrievals under the assumptions made here". On the other hand, the data are monthly averages, and for individual scenes, I expect much larger differences. Therefore, I'd suggest to add histograms of differences to the mean values for a more balanced view. Thank you for the suggestion. Indeed, the effects of cloud correction on the NO₂ retrieval is generally small over the polluted regions. It is challenging to compare pixel-by-pixel differences between OMI and TROPOMI due to their differing spatial sampling. Even when measurements are taken over similar locations, the effects of cloud correction can vary as a result of differences in solar and viewing geometries between the two sensors. Instead of a direct comparison, we have included maps in the revised appendix showing the maps of the average cloud correction effects for each approach, and results show that the cloud correction effect is generally within $\pm 20\%$.

We have rephrased this paragraph in the revised manuscript:

"The impact of cloud corrections on the NO₂ AMF is generally within $\pm 20\%$ (see Figure A5). All corrections exhibit a systematic positive bias over ocean, whereas over land, the effect is comparatively minor, except in tropical regions, where most cloud products introduce a negative bias. As shown in Fig.18(a), the average impact of cloud correction for the selected polluted regions ranges from -6% to 11%, depending on the cloud product applied. The AMF difference resulting from various cloud corrections can exceed 10%. However, these values remain well below the typical uncertainty associated with tropospheric NO₂ AMFs.\citep{Boersma2004}."

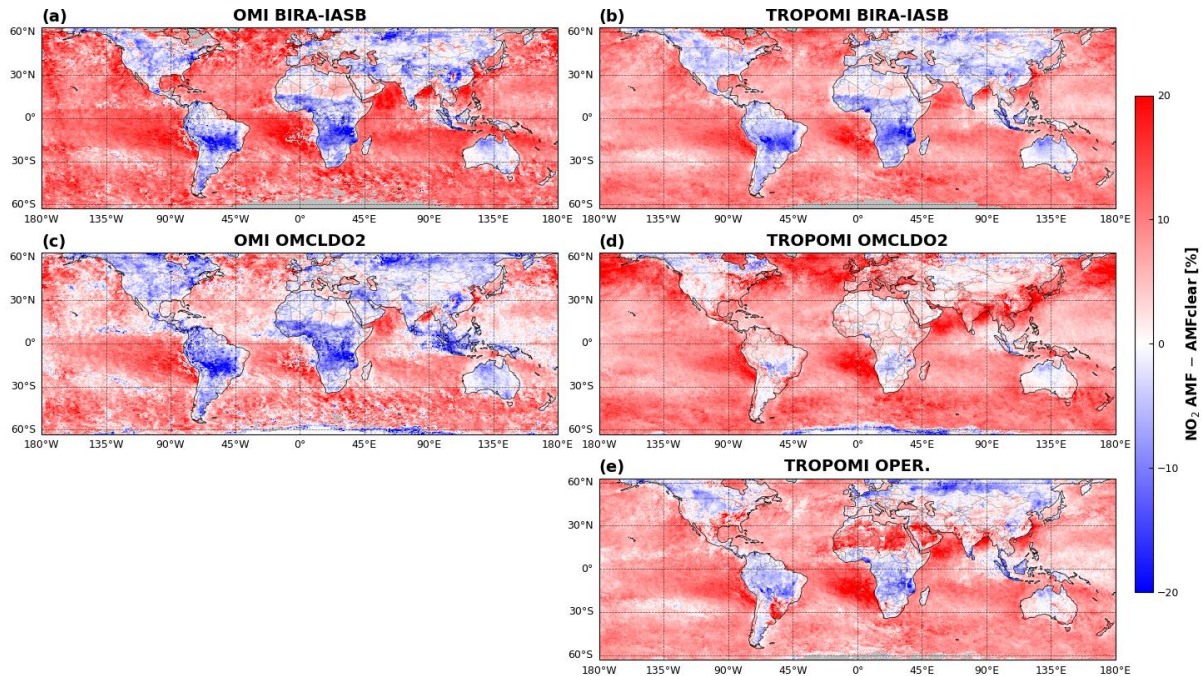


Figure A5: Monthly average impact of cloud correction on the tropospheric NO₂ retrievals from OMI (left) and TROPOMI for October 2018. The NO₂ AMF is calculated using identical retrieval settings, differing only in the cloud correction approach applied. Data are gridded at a spatial resolution of 0.5°, including only observations with a cloud radiance fraction below 0.5.

Finally, the results in Fig. 18b are quite surprising when comparing the cloud corrections TROPOMI-BIRA and operational – with the exception of Eastern China, they always have opposite sign! I think that warrants more discussion than just referring to “sampling effects”. How can we trust cloud corrections at all, if two different, state of the art approaches lead to opposite effects?

Fig. 18b shows the NO₂ VCDs, each normalized by the mean value of the five retrievals in the same region. This normalization is applied due to the large variability in NO₂ VCD values among different regions, and it helps to better highlight the relative differences caused by various cloud correction methods for each region.

A clear inverse correlation is observed between AMF corrections and NO₂ VCD retrievals for the three TROPOMI products (since $VCD = SCD/AMF$), as well as for the two OMI retrievals. The correlation between OMI and TROPOMI data is slightly weaker, primarily due to differences in sampling.

We have rephrased the paragraph in the revised manuscript:

“The NO₂ VCDs generally exhibit an inverse relationship with the effect of cloud corrections, particularly for the three TROPOMI retrievals. This correlation is somewhat weaker when comparing OMI and TROPOMI, which may be influenced by sampling differences between the two sensors.”

Detailed comments:

L28: ... most are partially covered by clouds.

Done

L31: wasn't the IPA assumption already used in Martin et al., 2002?

Yes, we included it, as the IPA assumption was already used in Martin et al., 2002.

L37: Although most people will know OMI, I think a very short introduction of OMI and in the next paragraph TROPOMI is needed here

We have added the following paragraph for OMI:

“The Dutch-Finnish-built OMI, a key payload aboard the NASA Aura spacecraft, is a nadir-viewing, wide-swath, push-broom imaging spectrometer designed for daily global monitoring of tropospheric composition.”

And also, for TROPOMI:

“TROPOMI, aboard the Sentinel-5P platform, is the first Copernicus mission dedicated to atmospheric monitoring, providing daily city-scale measurements for air quality assessment, ozone and UV radiation monitoring, and climate observation and forecasting.”

L38: Not sure if a trace gas with an exponential mixing ratio profile should be called “well mixed”. What about “with a known vertical distribution”?

Thanks for the suggestion and corrected it.

L40: “collision-induced absorption” sounds a bit strange as the absorption of the photon is not caused by the collision of the molecules, just the collisional complex has an absorption cross-section which has larger values at this wavelength.

Yes, we rephrased it as: The OMCLDO2 cloud product uses satellite measurements of the O2–O2 collision complex absorption feature centered at 477 nm.

L44: There is an imbalance in the discussion of OMI and TROPOMI here, as for OMI, cloud fraction retrieval is not explained

We expand upon the description of the OMI cloud retrievals as follows:

“Both algorithms use the independent pixel approximation, which characterizes pixel reflectance as a weighted combination of cloudy and clear-sky parts. This approach enables the determination of the effective cloud fraction rather than the geometric cloud fraction. Due to limited spectral information in the O2–O2 absorption band and the RRS process that are used for cloud pressure retrieval, the cloud is modeled as a Lambertian reflector with a fixed albedo of 0.8. Consequently, only the pressure level of this Lambertian cloud is retrieved.”

L99: “consistently sized rows” – not clear what is meant with this

We rephrased this sentence:

“The swath is divided into 77 to 450 across-track rows, with the binning factor adjusted to ensure similar spatial size for each row.”

L120: Please give full version number of lv1 product

Add: OMI processor version: 2.0.8.4/24861; TROPOMI: processor version: 2.1.0.25042

L140: ...can implicitly correct... => ... can implicitly correct part of the ...

Corrected

Figure 1: 10E-46 on y-axis label

The O₂-O₂ absorption cross-section values are scaled by 10⁴⁶, as indicated by the y-axis title ($\times 10^{46}$ cm⁵ molecule⁻²).

Figure 2: Which cloud fraction is used for (c) and (f)?

BIRA-IASB cloud fraction. Added it.

L225: Were the data also filtered for sun glint?

Not in this case. We investigated this by analyzing data within a selected latitude range that excludes regions affected by sun glint and found the results to be consistent with those obtained using our current approach. In addition, including a larger dataset helps improve the signal-to-noise ratio.

L259: ... at the 465 ... => ... at 465 ...

Corrected

L265. Add horizontal resolution of the model

Done (with horizontal resolution of 0.75°x0.75°)

L312: I do not understand, how this reduces interpolation errors, and also did not find any additional explanation in Wang et al, 2020. Can you please explain?

Linear interpolation is commonly used in the LUT-based approach. The O₂-O₂ SCDs exhibit a strong nonlinear dependence on VZA/SZA for high geometry angles, which can lead to relatively large interpolation errors. In contrast, the O₂-O₂ VCDs show only a weak dependence on geometry, resulting in smaller uncertainties due to interpolation.

L327: ... proportionally to with the ... => ... proportionally with ...

Corrected

L375: ... slightly highly ... => ... slight high ...

Corrected (slightly high)

L418: ... the algorithm is not sensitive to the high ... => ... the algorithm is not sensitive under high ...

Corrected

Figure 10: There are clear orbital structures in the western part of the TROPOMI image and in many places of the OMI images, both for cloud fraction and cloud pressure. Please discuss.

We have added:

“Over low-latitude ocean regions, distinct orbital structures are visible in the western part of the satellite swath, primarily due to sun-glint effects. These effects can lead the O2–O2 cloud retrieval to overestimate cloud fraction and potentially result in artificially low cloud pressure values.”

L481: Isn't that just a geometric effect, that apparent cloud fraction increases over broken clouds under slant view if clouds are 3d-objects?

Yes, there is a geometric effect. The apparent cloud fraction tends to increase under slant viewing angles due to vertical extent of clouds. However, 3D cloud structures may introduce both negative (due to shadowing) and positive biases in the cloud fraction retrieval.

Based on synthetic analysis of a scene containing a 1D cloud layer (Yu et al., 2022), the retrieved cloud fraction increases with SZA/VZA, primarily due to increased scattering by clouds along the longer light path.

We rephrased this:

“The cloud fraction values increase towards the edges of the swath, likely due to factors such as geometric effects and enhanced cloud scattering along the slant path.”

L489: Shouldn't we expect a bias in OMI cloud fractions as the pixels are larger than those of TROPOMI?

In principle, TROPOMI observations include more cloud-free pixels than OMI due to TROPOMI's higher spatial resolution. However, we do not expect a bias in the average cloud fraction between the two sensors, as the cloud fraction retrieval is based on the Independent Pixel Approximation (IPA) assumption, and the mean value does not depend on pixel size.

L524: I think it would be worthwhile to point out, why you used the 0.2 threshold – I assume that's because this corresponds to 50% cloud radiance fraction, and therefore is the limit used in the tropospheric NO2 discussion. This point is then relevant when discussing figures such as Figure 16a, where large discrepancies are found in exactly the range of values relevant for cloud correction in trace gas algorithms.

Yes, and we added a sentence in section 4.1.1:

“Tropospheric NO2 retrieval from satellite measurements typically excludes pixels affected by clouds. Such pixels are defined as having a cloud radiance fraction greater than 0.5, which corresponds to an effective cloud fraction of approximately 0.15–0.2.”

L579: Why is weighting with cloud fractions a good idea? I think that this artificially makes results look better, as high cloud fractions show better agreement (Figure 13) and weighting will bias everything towards large cloud fractions.

From a technical perspective, the weighted average provides a more appropriate metric for cloud pressure comparison than the simple average. When the dataset are grouped by the average TROPOMI cloud fraction within each grid cell (< 0.2 and > 0.2), the low cloud fraction cases exhibit greater scatter. Nevertheless, the overall conclusions remain largely unchanged, as demonstrated below. Furthermore, Section 4.1.4 investigates the relationship between cloud pressure and cloud fraction, indicating that the consistency between the two BIRA-IASB O2-O2 cloud pressure retrievals nearly independent on cloud fraction.

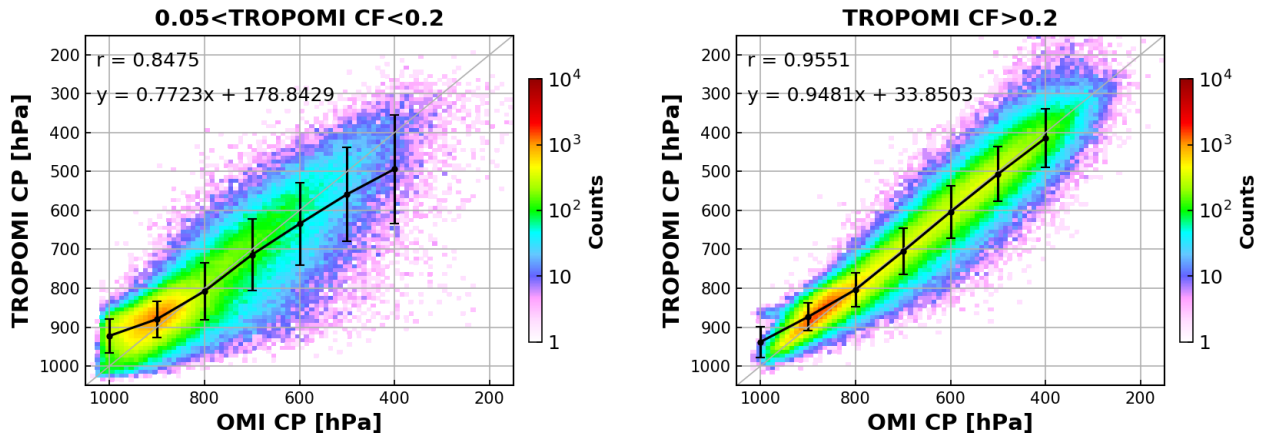


Figure: Similar to Figure 19(d), but showing data are grouped based on the average TROPOMI cloud fraction: < 0.2 (left panel) and > 0.2 (right panel).

Figure 17: remove “are considered”

Done

Figure 19: Figure headers “select data” => “selected data”

Done

Figure 20: axis labels “refletance” => “reflectance”

Done

Reference

- Kleipool, Q. L., Dobber, M. R., de Haan, J. F., & Levelt, P. F. (2008). Earth surface reflectance climatology from 3 years of OMI data. *Journal of Geophysical Research Atmospheres*, *113*(18), 18308. <https://doi.org/10.1029/2008JD010290>;CTYPE:STRING:JOURNAL
- Tilstra, L. G., De Graaf, M., Trees, V. J. H., Litvinov, P., Dubovik, O., & Stammes, P. (2024). A directional surface reflectance climatology determined from TROPOMI observations. *Atmospheric Measurement Techniques*, *17*(7), 2235–2256. <https://doi.org/10.5194/AMT-17-2235-2024>,
- Yu, H., Emde, C., Kylling, A., Veihelmann, B., Mayer, B., Stebel, K., & Van Roozendaal, M. (2022). Impact of 3D cloud structures on the atmospheric trace gas products from UV–Vis sounders – Part 2: Impact on NO_2 retrieval and mitigation strategies. *Atmospheric Measurement Techniques*, *15*(19), 5743–5768. <https://doi.org/10.5194/amt-15-5743-2022>

