Response to Reviewer 2 (Second Round)

Manuscript ID: egusphere-2025-5580

Title: Retrieving Stratospheric Ozone Profiles from OMPS Limb Profiler Measurements

Author(s): Fang Zhu et al.

Congratulate the authors of the manuscript for the extensive re-work implemented in the paper and for positively accepting the comments provided in the first round. I think the quality of the manuscript has been improved with respect to the first submission. I still have two major points that need to be addressed and some minor/technical considerations that you can find below.

Response: We sincerely thank you for your continued efforts in reviewing our manuscript and for your encouraging words. We greatly appreciate your recognition of our work. Below, we provide a point-by-point response to the remaining major points and minor technical corrections. All modifications in the revised manuscript have been marked for easy identification.

Major points

Point 1: The errors analysis has been substantially improved but the paragraphs from line 262 to 279 needs a major revision. First, if the objective is to assess the sensitivity to the a-priori, then you could skip lines 262-264, as AK are meant to assess, as you say, the sensitivity to the true profile and not to the a-priori. I suggest to move this to the description of MART, mentioning that the algorithm doesn't explicitly provide AK and directly start with "We assess the sensitivity of the retrieval to the prior….".

Fig. 4a is still not consistent with 4b: according to the right panel, the error from perturbing the a-priori profiles is small outside the tropical UTLS. As a consequence, the sensitivity of the retrieved profile to the a-priori is small in the middle stratosphere and A0 should also show close to zero peaks above 15 km. The sensitivity to the a-priori gets larger in the lowermost altitudes and above 35 km, as your retrieval has

not enough information from Vis radiance. Unfortunately, Fig. 4a shows the opposite. The only reason I can think of, is that you are plotting the wrong quantities: can you specify what is δx and δx0 in Eq.6? In my opinion the correct quantity for δx is the difference between the profile retrieved with the perturbed a-priori and the profile retrieved with the unperturbed a-priori. This should be small in the middle stratosphere and getting larger at the altitude boundaries.

Response 1: We thank you for this critical observation. We have carefully addressed all aspects of this comment as described below.

1. Moving the AK-related sentence to the MART description

We agree with you that the discussion of formal averaging kernels (AKs) is not needed in the error analysis section. We have moved the relevant sentence to Section 3.2 (Multiplicative algebraic relaxation technology), where the MART algorithm is described. The error analysis section now directly starts with: "We assess the sensitivity of the retrieval to the prior profile through a perturbation-based approach."

Modifications in Manuscript:

Section 3.2, Lines 199-201: "The sensitivity of retrieval to the true state and the contribution of prior information can be formally described through the averaging kernel and measurement response (Rodgers, 2000; von Clarmann et al., 2020). However, unlike Optimal Estimation (OE) approaches, the MART algorithm used in this study does not produce formal averaging kernels."

Section 4.1, Lines 266: "We assess the sensitivity of the retrieval to the prior profile through a perturbation-based approach."

2. Clarifying Eq. (6) and the definition of $\partial\hat{\boldsymbol{x}}$ and $\partial\boldsymbol{x}_0$

The definitions in Eq. (6) were unclear. We have revised the text to explicitly define:

$\partial\boldsymbol{x}_0$ is the +5% perturbation applied to the prior at a single altitude.

$\partial\hat{\boldsymbol{x}}$ is the resulting difference between the retrieval using the perturbed prior and the retrieval using the unperturbed prior.

We have confirmed that this is what we computed.

Modifications in Manuscript:

Section 4.1, Lines 272-273: "Specifically, $\partial \boldsymbol{x}_0$ is the perturbation applied to the prior, and $\partial \hat{\boldsymbol{x}}$ is the difference between the retrieval using the perturbed prior and the retrieval using the unperturbed prior."

3. Addressing the inconsistency between Fig. 4a and Fig. 4b

Upon re-examining our calculations, we identified a minor implementation issue in our processing code that affected the numerical computation of the prior sensitivity matrix $\mathbf{A}_0$. The conceptual definition in Eq. (6) remains correct, but the numerical implementation had a small error that led to the inconsistency.

We have now corrected the implementation and recomputed the prior sensitivity analysis. As you correctly expected, the revised Fig. 4a now shows the influence is now largest below 15 km, and approaches zero above 20 km. This is now fully consistent with the prior-induced retrieval errors shown in Fig. 4b. The revised text have been updated accordingly.

Modifications in Manuscript:

Section 4.1, Lines 278-280: Rewrote the interpretation of Fig.4a to accurately reflect the prior influence patterns.

"In the lower stratosphere (below 20 km), the response amplitudes are strong, indicating that strong prior dependence due to reduced measurement information content under weak limb-scattering signals."

Section 4.1, Lines 292: Figure 4a has been completely replotted to illustrate the distribution pattern of a priori profile influences. The new figure shows less prior influence above 20 km, consistent with Fig. 4b.

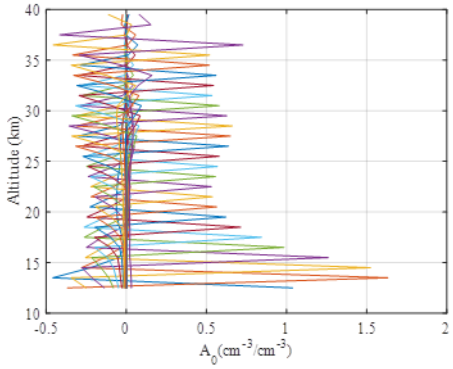

Figure 4. (a) Distribution of $\mathbf{A}_0$ for measurements at 2.2 ℃.

Point 2: It is not clear to me what has been done with the profiles affected by clouds. Especially in the conclusion, the authors stress that the lower stratospheric biases are linked to the presence of clouds and that the profile is constrained to the a-priori. For the validation, have you included values at altitudes affected by cloud? In case you have, I strongly suggest to filter out these values in the validation, to avoid obvious biases that come from the impossibility to actually retrieve ozone at those altitudes. This might already reduce some of the biases in the tropics. Why do you expect ozone abundances above the cloud top to be also overestimated by 25 % (as you say at line 547)? Other than aerosols, another source of biases could be the usage of an outdated ozone cross-section, and not having taken into consideration NO2 in the forward modelling.

Response 2: We thank you for raising this important point. We have carefully reviewed our validation procedures and provide the following clarifications and revisions.

1. Regarding validation and cloud filtering

In validation, we do not include cloud-affected altitudes. For each collocated profile, only altitudes above the detected cloud top height are included in the comparison. Altitudes at or below the cloud top are excluded. We have now made this explicit in Section 4.2.

Modification in Manuscript:

Section 4.2, Lines 350: "For validation, only altitudes above the detected cloud top height are included in the comparison."

2. Regarding the 25% overestimation above cloud tops

The 25% value is derived from a sensitivity test comparing two strategies at the same altitude above the cloud top height (e.g., 17.5 km):

Strategy A (our method): Retrieval is performed over the full 12–40 km range. When a cloud is detected at a given CTH (e.g., 16.5 km), the multiplicative update factors for altitudes below the CTH are set equal to the multiplicative update factor from the nearest altitude above the CTH (e.g., the factor at 17.5 km is applied to the 12.5–16.5 km range). The multiplicative update factors are as follows.

$$\alpha_i = \sum_j \left(\frac{y_j^{\text{obs}}}{y_j^{\text{mod}}} W_{ji} \right)$$

Strategy B (reference for comparison): Retrieval is performed only for altitudes above the CTH (starting from the nearest grid point above the CTH, e.g., 17.5 km). Altitudes at or below the CTH are not retrieved and have no prior profile; they are simply truncated.

The relative difference in the retrieved ozone at 17.5 km between Strategy A and Strategy B is approximately 25%. Figure 1 compares the ozone retrieval results from the two cloud-handling strategies at 12 ℃N latitude for orbit 51220, which intuitively illustrates the systematic deviation in ozone profile retrieval induced by different cloud processing schemes.

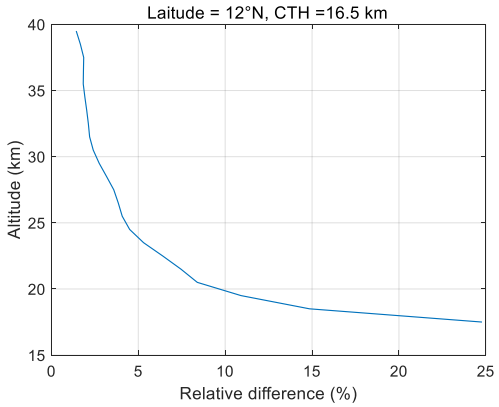

Figure 1. Relative difference of ozone retrievals derived from two different cloud-handling strategies at 12 ℃N latitude for orbit 51220.

Strategy B represents an extreme case where the retrieval is completely decoupled from the cloudy region, while Strategy A propagates the multiplicative update factor from above the cloud downward. The 25% difference quantifies the sensitivity of the retrieval to the cloud handling assumption and reflects the systematic bias introduced by propagating cloud-top information into the lower atmosphere. We have clarified this in Section 3 and Section 5.

Modification in Manuscript:

Section 3.2, Lines 192 and 198: We have added the description of the multiplicative update factor.

Section 3.3, Lines 221-222: "Retrievals are not performed below the cloud top

height, while the multiplicative update factor above the cloud top is propagated downward into the cloudy region."

Section 5, Lines 548-552: "A sensitivity test on a representative profile (equatorial region) demonstrates that, at the same altitudes above the CTH, our method—which propagates the multiplicative update factor from above the cloud top into the cloudy region—produces ozone concentrations approximately 25% higher than the scheme with retrieval limited only to altitudes above the cloud top. This result quantitatively reveals the potential systematic impact of cloud constraints on ozone profile retrievals under cloudy conditions."

3. Regarding other bias sources (cross-sections and NO_2)

We agree with you that outdated cross-sections and neglecting NO_2 could contribute to biases. We have added these points to the future work discussion in the Conclusions.

Modifications in Manuscript:

Section 5 (Conclusions), Lines 554-556**:** "Beyond aerosol effects, additional bias contributions arise from ozone absorption cross-sections that incompletely account for temperature-dependent uncertainties, as well as the neglect of NO_2 absorption in the current forward model."

Section 5 (Conclusions), Lines 562-563: "Further model improvements will include updating the ozone absorption cross-section database and incorporating NO_2 absorption into the forward model."

Minor considerations

Point 1: I still don't find really informative the plots 7, 9, 12, 15, but I leave it to the discretion of the authors. I also point out the fact that using Eq. 7 would inflate the resulting values in panels (b) of these pictures, as the very large relative differences in the tropical UTLS are possibly having a large weight in the annual mean relative difference that you are plotting. If you use the mean of the absolute differences and then divide by the mean profile this would be reduced.

Response 1: We acknowledge your concern. We have decided to retain panels (a) of these figures as they provide essential context about the absolute scale and vertical

structure of ozone profiles, which aids readers in interpreting the relative differences in panels (b). Regarding Eq. (7), we agree that the very large relative differences in the tropical UTLS can influence the annual mean. However, Eq. (7) is the standard formula for relative difference used in the majority of satellite validation studies (e.g., Arosio et al., 2018), and we prefer to maintain consistency with the literature. No changes have been made to the figures or Eq. (7).

Point 2: The description of Fig. 11 raises a couple of questions. First, the positive bias at southern high latitudes is attributed to surface albedo biases: have you retrieved surface albedo as well? I haven't found this information in the retrieval description. If you haven't, then the missing albedo retrieval can also cause biases in the lower stratosphere. Second, why is here introduced the transition between UV and Vis ranges if you only used the visible range? I think that the positive bias above 35 km is simply related to the lack of sensitivity of the visible range at these altitudes.

Response 2: We thank you for this question.

1. Regarding surface albedo retrieval

We acknowledge that we do not perform a full multi-parameter retrieval of surface albedo. Instead, we derive an effective scene reflectance from the radiance at 675 nm. As described in Section 4.1， Lines 262-263: "Furthermore, the scene reflectance was determined directly from OMPS/LP radiance measurements at 675 nm, ...". This is a common approximation in limb-scattering retrievals. Our approach is consistent with methods used in other limb retrieval algorithms (e.g., Arosio et al., 2018). This scene reflectance is used as the surface albedo input for the SCIATRAN radiative transfer model. The term "scene reflectance" in Section 4.1 and "surface albedo" in the Fig. 11 description refer to the same quantity—an effective albedo derived from the OMPS/LP measurements.

Thus, the positive bias observed over Antarctica may indeed be linked to inaccuracies in this retrieved albedo, particularly in polar regions where surface reflectance is highly variable and seasonally dependent. We have revised the texts to make these clearer.

Modification in Manuscript:

Section 4.1, Lines 262-263:“Furthermore, the effective surface albedo was determined directly from OMPS/LP radiance measurements at 675 nm (referred to as scene reflectance in the NASA product),…”

Section 4.3, Lines 430-431:“Conversely, a positive bias is observed over Antarctica, possibly linked to inaccuracies in the retrieved effective surface albedo, particularly in polar regions with high seasonal variability.”

Strictly speaking, we retrieve a scene reflectance from the OMPS/LP radiance measurements. This scene reflectance accounts for both surface and atmospheric effects. In forward model, we approximate it as a Lambertian surface albedo—a common simplification in limb-scattering retrievals (e.g., Arosio et al., 2018). Therefore, the retrieved value is referred to as ‘scene reflectance’ when describing the measurement product, and as ‘effective surface albedo’ when describing its role in the model. To clarify the description and avoid ambiguity throughout the manuscript, we have unified all relevant terms as the effective surface albedo.

2. Regarding the UV/Vis transition discussion

Since we only use the visible spectral range, discussing the UV/Vis transition is inappropriate. We have removed this statement and replaced it with a correct explanation: the positive bias above 35 km is due to the inherently limited sensitivity of the visible spectrum at high altitudes.

Modifications in Manuscript:

Section 4.3, Lines 432-433: “Above 35 km, the retrievals exhibit a positive bias in the tropics. This bias arises from the inherently limited sensitivity of the visible spectrum at these altitudes, where ozone absorption is weak and measurement signals become dominated by noise and stray light.”

Technical corrections

Point 1: L14-15: You could introduce first limb profiler (LP) at line 14 and then use it at line 15.

Response 1: Corrected as suggested. “Limb profiler (LP)” is now introduced at line

14, and “LP” is used at line 15.

Modification in Manuscript: Abstract, Line 14-15.

Point 2: L30: “in low-altitude tropical regions.” → ”in the tropics at low altitudes.”

Response 2: Corrected as suggested.

Modification in Manuscript: Abstract, Line 30.

Point 3: L60: What does “with operations” mean?

Response 3: The unclear phrase “with operations” has been removed from the sentence.

Modification in Manuscript: Section Introduction, Line 60.

Point 4: L154: “adheres” → “corresponds”

Response 4: Corrected as suggested.

Modification in Manuscript: Section 3.1, Line 154.

Point 5: L155: Add “ensuring” before consistency

Response 5: Corrected. The text now reads “thereby ensuring consistency”.

Modification in Manuscript: Section 3.1, Line 155.

Point 6: L161: The first sentence of this paragraph is not really informative, I would remove it.

Response 6: The first sentence of the paragraph has been removed.

Modification in Manuscript: Section 3.1, Line 161.

Point 7: L173: Add “perturbed” after “aerosol extinction profiles”

Response 7: Corrected. The text now reads “perturbed aerosol extinction profiles”.

Modification in Manuscript: Section 3.1, Line 173.

Point 8: L174: “When the aerosol varies… the radiance profiles is…” → “We perturbed the aerosol extinction profiles with factors from 0.1 to 10 and we found that the radiance profile is…”

Response 8: The sentence has been rewritten as suggested.

Modification in Manuscript: Section 3.1, Line 174.

Point 9: L182: I suggest “Variations in radiance and CTV due to perturbed aerosol extinction coefficients as reported in the legend”.

Response 9: The figure caption has been revised accordingly.

Modification in Manuscript: Section 3.1, Line 182.

Point 10: L199: Add “the” before “cloud top height”

Response 10: Corrected. The text now reads “the cloud top height”.

Modification in Manuscript: Section 3.3, Line 203.

Point 11: L217: I would remove “During the ozone retrieval process,” and leave the rest of the sentence.

Response 11: The phrase has been removed as suggested.

Modification in Manuscript: Section 3.3, Line 221.

Point 12: L226: “as the forward modelling” → “as forward model”

Response 12: Corrected as suggested.

Modification in Manuscript: Section 3.4, Line 230.

Point 13: L233: “referenced from the research results of” → “taken from”

Response 13: Corrected as suggested.

Modification in Manuscript: Section 3.4, Line 237.

Point 14: I would remove the last sentence at line 244-245.

Response 14: The last sentence at lines 244-245 has been removed.

Modification in Manuscript: Section 3.4, Line 248.

Point 15: L251: “achievements” → “studies”

Response 15: Corrected as suggested.

Modification in Manuscript: Section 4.1, Line 254.

Point 16: L309: “relative to” → “with respect to”

Response 16: Corrected as suggested.

Modification in Manuscript: Section 4.1, Line 311.

Point 17: L358: “lower boundaries of retrieval” → “lower retrieval boundaries”

Response 17: Corrected as suggested.

Modification in Manuscript: Section 4.2, Line 361.

Point 18: L369: “may be caused” → “is caused”

Response 18: Corrected as suggested.

Modification in Manuscript: Section 4.2, Line 372.

Point 19: L385: “The MLS obtained” → “MLS provides”

Response 19: Corrected as suggested.

Modification in Manuscript: Section 4.3, Line 388.

Point 20: L400: “with in altitude” → “with altitude”

Response 20: Corrected as suggested.

Modification in Manuscript: Section 4.3, Line 403.

Point 21: L419: Can you please better describe what is shown in Fig. 11? The sentence is hard to read.

Response 21: The sentence describing Fig. 11 has been rewritten for clarity.

Modification in Manuscript: Section 4.3, Line 422-423:

“Fig. 11 depicts the altitude-dependent relative differences between retrieved profiles and MLS zonal means in 1 °latitude bins across the three selected periods.”

Point 22: L425: “retrieval uncertainties.” → “the discrepancies in relative values.”

Response 22: Corrected as suggested.

Modification in Manuscript: Section 4.3, Line 428.

Point 23: L451: “(/cm3)” → “(molecule/cm3)”

Response 23: Corrected as suggested.

Modification in Manuscript: Section 4.4, Line 454.

Point 24: L512: “bias are” → “bias is”

Response 24: Corrected as suggested.

Modification in Manuscript: Section 4.5, Line 515.

Point 25: L523: “applies the ozone…” → “applies an ozone…”

Response 25: Corrected as suggested.

Modification in Manuscript: Section 4.3, Line 526.

Please ensure that the colour schemes used in your maps and charts allow readers with colour vision deficiencies to correctly interpret your findings. Please check your figures using the Coblis – Color Blindness Simulator (https://www.color-blindness.com/coblis-color-blindness-simulator/) and revise the colour schemes accordingly. --> Fig. 14

Response: We have revised the colors in Figure 14 from red to orange and from green to cyan to improve accessibility for readers with color vision deficiencies. Distinct

line styles are retained as an additional means of differentiation.

We appreciate the reviewers' and editor's thorough evaluation of our manuscript. We believe the revisions have substantially improved the paper and have addressed all remaining concerns. We thank you again for your time and expertise, and we look forward to your final decision.

Sincerely,

Fang Zhu

On behalf of all authors