

- **RC1:**
- Manuscript Review - Maratt Satheesan et. al, 2025
- Journal: EGU sphere
- Date Submitted: 2 April 2025
- Title: Extension of the S5P-TROPOMI CCD tropospheric ozone retrieval to mid-latitudes
- Authors: Maratt Satheesan, Eichmann, Weber, Van Malderen, Stauffer, and Tarasick
- Summary:
- This paper presents the first application of a global convective cloud differential (CCD) approach outside of the tropics, where the standard Cloud Slicing and CCD algorithms have been used for decades with limited geographic range (i.e., confined to the tropics). The multi-year mean product produced with the new algorithms agree well with the established approaches in the tropics. The advantage of the new approach lies in its ability to produce results outside of the tropics, where clouds tend to be lower. Having such a product validated and regularly available would be of benefit to tropospheric ozone trend analyses and the identification of influences from large scale biomass burning events.
- In its current form, I found this paper challenging to read and review. Overall, the paper could stand some tightening up and a sharper focus on the results that the authors wish to communicate. At present, I found the paper too long, often repetitive, and too broad in scope.
- Up front in the paper, it would be nice to know:
- What product does this new approach produce? With what temporal and spatial resolution?

Ans: We sincerely thank the reviewer for his/her time and thoughtful comments on the manuscript. We have carefully considered all suggestions and provide our responses and clarifications below.

The CLCD algorithm produces daily tropospheric column ozone (TCO) from the surface up to 450 hPa on a $0.5^\circ \times 0.5^\circ$ spatial grid. The product is derived from operational TROPOMI total ozone and cloud measurements. The novel aspect is that this approach is the first that is applicable outside the tropics and provides near-global coverage up to 60°N/S .

- Under what conditions is this new approach useful? Seasons? Cloudy/clear scenes? Latitudes?

Ans: The method is primarily designed for mid-latitudes (up to 60 degree), where conventional CCD approaches are not available ($<20^\circ\text{N/S}$) due to the strong spatial variability in stratospheric ozone. It performs best under conditions with sufficient availability of cloudy scenes ($\text{CF} \geq 0.8$)

within the larger local cloud sector and clear-sky ($CF \leq 0.2$) in the smaller retrieval grid cell.

The adaptive selection between CLCD-C and CLCD-T allows the method to be applied across a range of cloud conditions, including both homogeneous and variable cloud fields. However, performance may be reduced in regions or seasons with persistent cloud cover, limited cloud variability, or insufficient sampling.

- Over what time period must results be averaged to be useful/reliable?

Ans: The product is generated at daily resolution; however, its reliability depends on the availability of sufficient clear-sky and cloudy observations within a grid cell. In regions with limited sampling (< 20 “cloudy” measurements per grid cell), temporal averaging (e.g. monthly means) improves robustness by reducing random variability and sampling-related uncertainties. Therefore, while daily values provide useful insights, monthly or seasonal averages are generally more suitable for quantitative analysis.

- What are the uncertainties in the product and how are they impacted by geographic locale, temporal changes, and meteorological conditions?

Ans: The uncertainty in the CLCD-TCO product is estimated to be approximately ~ 4 DU on average, with contributions from total ozone, Above Cloud Column Ozone (ACCO), cloud parameters, and sampling.

The uncertainty varies with:

- Geographic location: Higher uncertainties occur at higher latitudes due to increased stratospheric ozone variability.
- Temporal variability: Uncertainty is typically larger during winter and spring, when dynamical variability is stronger.
- Meteorological conditions: Regions with limited clear-sky or cloudy scenes, or with highly variable cloud-top heights, show increased uncertainty due to reduced sampling and less stable ACCO or TOZ (Total Ozone under clear sky scene).

These dependencies are discussed in detail in Section 4.2 (Uncertainty Budget) (**Line number; 154**) and Section 5.1.1 (causes of bias and variability in CLCD-retrievals) (**Line number 220**).

- In its present form, I feel unclear on what the authors are trying to communicate in this paper. Is this a techniques paper or is there science to be gleaned from their analysis?

Ans: The main objective of this paper is to present and evaluate a new methodological approach (CHORA-CLCD) for retrieving tropospheric ozone from TROPOMI globally. The focus is therefore on the development and validation of the algorithm.

Additionally, we include tropospheric ozone maps to show a few possible applications of the method under different atmospheric conditions. These are intended to provide context and demonstrate the behavior of the retrieval rather than to present a detailed scientific investigation of

tropospheric ozone variability.

- I had trouble following the use of cloud free and cloudy regions to determine a TCO. And I'm not sure how the authors' definition of the TCO – surface to 450 hPa – relates to prior definitions for comparison of the product. What fraction of tropospheric ozone is found between the surface and 450 hPa vs the column from the surface to the tropopause?

Ans: The CLCD product represents the ozone column between the surface and 450 hPa rather than the full tropospheric column extending to the tropopause. This definition was chosen because low-level clouds dominate at mid-latitudes, making 450 hPa a practical and well sampled reference altitude.

Furthermore, the TOAR-II (<https://igacproject.org/activities/TOAR/TOAR-II>) adopts 450 hPa as a reference pressure level, recognizing it as a standard atmospheric pressure level commonly used in atmospheric studies to represent the lower and mid-troposphere (Jenkins et al., 2012; Pope et al., 2024). Utilizing this common reference level promotes consistency in data comparisons and analyses across various studies, enhancing our understanding of tropospheric ozone dynamics.

Jenkins, G. S., Ndiaye, S., Gueye, M., Fitzhugh, R., Smith, J. W., and Kebe, A.: Lower/middle tropospheric ozone variability in Senegal during pre-monsoon and monsoon periods of summer 2008: Observations and model results, *Journal of Atmospheric Chemistry*, 69, 273–302, <https://doi.org/10.1007/s10874-012-9240-7>, 2012.

Pope, R. J., Rap, A., Pimlott, M. A., Barret, B., Le Flochmoen, E., Kerridge, B. J., Siddans, R., Latter, B. G., Ventress, L. J., Boynard, A., et al.: Quantifying the tropospheric ozone radiative effect and its temporal evolution in the satellite era, *Atmospheric Chemistry and Physics*, 24, 3613–3626, <https://doi.org/10.5194/acp-24-3613-2024>, 2024

We updated the text as “Because low-level clouds are more common outside the tropics, CLCD retrieves tropospheric ozone from the surface to 450 hPa (~5.5 km), rather than the 270 hPa reference level commonly used in tropical retrievals (Maratt Satheesan et al., 2024). This altitude range encompasses a substantial portion of the troposphere, where various dynamic atmospheric processes occur, including the rapid convective uplift of boundary-layer air, particularly in the tropics, and its transport into the upper troposphere through large-scale circulation, for example, via warm conveyor belts in the extra-tropics (Chen et al., 2012; Monks et al., 2015). The 450 hPa level provides a consistent reference for studying a substantial part of the troposphere and is also used in atmospheric studies and the Tropospheric Ozone Assessment Report Phase II (Jenkins et al., 2012; Pope et al., 2024) (TOAR-II, <https://igacproject.org/activities/TOAR/TOAR-II>). In the extratropics, the stratospheric contribution to ozone above 450 hPa can be substantial, particularly during winter (Williams et al., 2019). The common reference level ensures consistency in data comparison and analyses from various studies.” **(Line number; 44-53)**

- In addition, in the Section 5 - Validation and discussions - far too often, the authors make suppositions and call out “possible” and “likely” explanations for characteristics in their data

without or with meager evidence. Their claims seem stronger than their proof (if it is presented). I would like to see more connecting of the dots to demonstrate their claims match the evidence.

Ans: Please find the answers for the detailed comments below.

- I also have concerns about the error budget formulation and how this algorithm functions in regions of topographic variability. Please look at my detailed comments below.

Ans. Please find our replies below.

- Overall Recommendation:

I recommend against publishing this manuscript in the current form. A major rework that addresses my concerns (and those of the other reviewers) would improve the draft – if resubmitted, I would be willing to re-review a revised manuscript.

Detailed Comments (by line numbers)

- **Abstract:** Consider shortening and focusing the abstract on the key results and takeaways for the reader. Remove background information.

Ans: We have shortened the abstract.

- **31:** “It empahsises...” To what does “it” refer?

Ans: The sentence doesn’t exist due to the update of manuscript.

- **64:** reference is made to a “homogeneity criterion,” which I know is defined later in the paper. At this point, I am wondering what that means, however.

Ans: Added the following text: “Here, we present CLCD (CHORA Local Cloud Decision), an extension of CHORA for tropospheric ozone retrievals between 60°S and 60°N. CLCD dynamically selects between CLCD-C and CLCD-T based on the available cloud characteristics. CLCD-C uses climatological corrections, while CLCD-T directly derives ACCO using Theil–Sen regression. A total ozone homogeneity criterion is also applied: a retrieval is retained only when the standard deviation (1σ) of cloudy-sky total ozone ($CF \geq 0.8$) within the local reference sector is below 10 DU (discussed in Section 4)” **(line number 39 to 44)**

- **68-69:** “e.g., long-range transport of boundary layer air to the upper troposphere.” I’m not sure I completely understand this example. I think of air moving to the UT/LS region vertically quite rapidly in conditions of convective instability. In the UT/LS, it can be transported long distances. Perhaps the authors could rephrase to clarify the meaning.

Ans: changed the sentence to “This altitude range encompasses a substantial portion of the

troposphere, where various dynamic atmospheric processes occur, including the rapid convective uplift of boundary-layer air, particularly in the tropics, and its transport into the upper troposphere through large-scale circulation, for example, via warm conveyor belts in the extra-tropics (Chen et al., 2012; Monks et al., 2015). **(line number 46-49)**

Monks, P. S., Archibald, A., Colette, A., Cooper, O., Coyle, M., Derwent, R., Fowler, D., Granier, C., Law, K. S., Mills, G., et al.: Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer, *Atmospheric chemistry and physics*, 15, 8889–8973, 2015.

- **87:** “August 2019 (Ingmann et al., 2012).” Curious about the two dates here, with the reference to a paper 7 years prior to the date of application?

Ans: Removed the reference **(Line number; 64)**.

- **117-118:** regarding the conversion of ozone mixing ratio provides to columns in DU, the authors reference their own 2024 paper. Is the authors’ approach different than those used previously? Is it novel? Does it agree well with prior approaches? I think there’s probably a primary reference to cite here for this process...

Ans: The conversion from ozone volume mixing ratio to partial column in DU is based on the ideal gas law (calculation of air density and conversion to number density) and subsequent integration over the desired altitude range.

- **118:** You mention spatial collocation conditions for ozonesondes and TROPOMI data. What about the temporal coincidence criteria?

Ans: We compare monthly averages with those from sonde stations located in the same satellite grid box. Upon reviewing our data, particularly for subtropical and mid-latitude stations, we found that there were not enough temporally collocated data for reliable validation. Therefore, we decided to rely on temporally non-collocated data to ensure a more robust analysis.

- **132:** You reference McPeters et al, 2003, which appears to be an AGU presentation. I think the paper you want is McPeters et al. (2007). Also, is there something newer than this? The data that went into the McPeters et al. climatology is 20+ years old. Do you have any concerns about trends/drifts over the intervening years?

Ans: Yes. Changed to McPeters et al. (2007) **(Line number; 109)**. The trends in the upper troposphere are generally very small and do have only a minor effect.

- **138:** I think you should probably have a reference to Figure 2 somewhere around this point.

Ans: We agree. Added the reference to the figure in the main text **(line number 119)**

- **140-141:** You require a cloud-top-height greater than 2 km. Is this above sea level or about ground level?

Ans: Surface with respect to the geoid/MSL.

- **141-142:** You justify a circular reference area for the extratropics due to varying wind directions and mention that there is “no single dominant direction.” Do you have a reference to support this assertion or data to show? Have you tried different shaped regions? Might the shapes depend on the meteorological conditions? I can imagine a frontal boundary crossing through one of these regions with very different tropospheric ozone ahead of and behind the front. Have you tested the algorithms performance in such cases?

Ans: We did not systematically test different sector shapes, as such shapes would require reliable, high-resolution wind data for each retrieval, increasing algorithm complexity. A dynamically flexible sector may still sample air masses with heterogeneous ozone under rapidly evolving meteorological conditions.

To avoid the influence of frontal boundaries and strong horizontal ozone gradients, the algorithm applies the homogeneity criteria on total ozone within the reference sector. Retrievals failing these criteria are filtered and assigned a fill value, thereby limiting the impact of inhomogeneous conditions such as frontal passages.

- **146-147:** “... the common reference level or upper altitude limit for the tropical ozone column is 450 hPa (~5.5 km) instead of 270 hPa.” I’m a bit confused by this statement. I thought the clouds were higher in the tropics, so I am surprised the statement references a lower altitude (higher pressure) for tropical ozone column. Is this a typo?

Ans: Yes. Sorry for the confusion. We meant “tropospheric” instead of “tropical”. Changed the sentence to “Because low-level clouds are more common outside the tropics, CLCD retrieves tropospheric ozone from the surface to 450 hPa (~5.5 km), rather than the 270 hPa reference level commonly used in tropical retrievals (Maratt Satheesan et al.,2024). ” (**Line number; 44-46**)

- **163:** regarding the daily averaging in each grid box: the Sentinel-5P overpass is at 13:30 local time roughly. I guess some 0.5X0.5 grid boxes could have successive orbits in them...With a scan width of 2600 km (2.5 deg of latitude or >2.5 deg of longitude) and a pixel at 7 km X 3.5 km² in the middle, does the introduction of successive scans negatively impact the value assigned to a grid cell? Would you be better off using only pixels from the same overpass/scan, then interpolating in space between successive scans rather than computing a daily average?

Ans: Although successive Sentinel-5P orbits sample the same $0.5^{\circ} \times 0.5^{\circ}$ grid box for latitude above 25° N/S, the observations takes place within a narrow temporal window with only small contribution from the diurnal variation (~90 min). Daily averaging is applied to ensure robust sampling, particularly in mid-latitudes where clear-sky scenes are limited. Restricting the analysis to a single overpass would significantly reduce data coverage.

- **165-166:** you assign a bad quality flag to negative data and substitute a “designated fill value” in the data set. Is information lost by not preserving the negative values? The

distribution should be informative as to the performance and reliability of the approach. How did you handle the error calculations for the data product in regions where there were negative values? Should not these negative values be included in the statistical analysis, including means? By eliminating the negative values, are you artificially biasing your data set to the high side?

Ans: Negative tropospheric ozone values are most probably caused by retrieval uncertainties, probably due to noisy ACCO data. We think, such cases therefore indicate retrieval failure rather than any meaningful atmospheric information. For the final data product, these values are replaced by a designated fill value and assigned a quality flag of 5 to clearly indicate unusable retrievals.

Statistical analyses, including mean biases, and standard deviations, are computed only using retrievals that meet all quality and homogeneity criteria (quality flags 1 to 4). Negative values are therefore excluded from these statistics by design, as their inclusion would not improve representativeness and could twist physically meaningful assumptions. Error estimates are derived from the valid retrieval data and are not computed in regions dominated by flagged (invalid) data. We understand that excluding negative values may slightly shift the data distribution.

We analysed the occurrence of negative TCO cases associated with overestimated ACCO for each region and year. On average over 2018--2022, negative TCO450 cases occurred in about 34% of the retrievals at midlatitude stations and about 24% in both subtropical and tropical regions. Negative TCO occurs more frequently at midlatitudes, which may be associated with the larger variability of stratospheric ozone at these latitudes, despite the applied homogeneity criterion.

- **168 - 170:** “TCO is computed only when...otherwise it is replaced with a fill value and assigned a quality flag of 5.” How was this criterion determined? I'm not sure how to reconcile its application with the procedure outlined in the prior paragraph which requires clear sky conditions? Also, again, how does this treatment of the data impact your uncertainty estimates?

Ans: The 10 DU homogeneity threshold for total ozone within the local cloud reference sector was chosen based on sensitivity tests and prior CCD-based studies, which show that stratospheric ozone variability exceeding this level leads to unreliable ACCO values and non-physical TCO values (e.g. Leventidou et al., 2016). The threshold therefore represents a compromise between retaining sufficient data sampling and sufficient stratospheric homogeneity.

The application of this criterion is consistent with the clear-sky requirement. While TCO is computed using clear-sky total ozone measurements ($CF \leq 0.2$), the homogeneity test is applied independently to cloudy scenes ($CF \geq 0.8$) within the local cloud reference sector to ensure that the derived ACCO is representative and not influenced by strong horizontal stratospheric ozone gradients. These two steps address different components of the retrieval.

As mentioned earlier, retrievals failing the homogeneity criterion are flagged and excluded from the uncertainty calculations. Consequently, the reported uncertainties reflect only physically consistent and robust retrievals. This filtering is also the primary cause of the data gaps observed in Fig. 5.

Leventidou, Elpida, Kai-Uwe Eichmann, Mark Weber, and John P Burrows (2016). “Tropical tropospheric ozone columns from nadir retrievals of GOME-1/ERS-2, SCIAMACHY/Envisat, and GOME-2/MetOp-A (1996–2012)”. In: Atmospheric Measurement Techniques 9.7, pp. 3407–3427. DOI: 10.5194/amt-9-3407-2016

- **Figure 2:** the Boulder ozonesonde station – This scene has significant variations in surface altitude. This box has altitude variations of ~100 m in the "flat" part to the east and 0.5 km to the immediate west with differences up to 3 km vertically just a bit further west but within 30 km! How does this algorithm work with such changes in topography?

Ans: Variations in surface altitude do not directly affect the CLCD algorithm, as the retrieval is based on column-integrated ozone quantities referenced to pressure levels rather than geometric altitude. The above-cloud column ozone (ACCO) is retrieved as a function of cloud top height/pressure and cloud fraction, making the method largely insensitive to surface elevation changes within the reference sector. The local cloud reference sector is used solely to characterize the stratospheric ozone column above optically thick clouds ($CF \geq 0.8$). These clouds typically exist well above the surface and therefore makes the ACCO independent from the underlying topography. Furthermore, the algorithm relies on cloud-top height variability and total ozone homogeneity criteria to ensure that only spatially consistent conditions contribute to the ACCO estimate.

- **175ff:** I am unclear at the formulation of this error budget. I assume these are calculated on the same 0.5X0.5 grid? Additionally, if this is a total uncertainty in the daily tropospheric column, but is derived from measurements made essentially only at 1330 local solar time, how do you account for variation within the troposphere throughout the rest of the day?

Ans: All uncertainty terms in Eq. (1) are computed consistently on the same $0.5^\circ \times 0.5^\circ$ grid used for the daily tropospheric ozone product. The terms N_{TOZ} and N_{ACCO} explicitly account for the number of valid clear sky total ozone and above-cloud ozone measurements contributing to each daily grid box and cloud sector, respectively. The reported uncertainty represents the contribution from measurement and retrieval uncertainty of the satellite derived daily tropospheric column ozone and sample statistics in the grid box and cloud sector. Since Sentinel-5P samples the atmosphere close to the local time (~13:30), the product represents early afternoon conditions.

- **211:** what is the temporal coincidence criterion for matches with ozonesondes? All the maps in the paper show multi-year averages. Can you compute a monthly average with a subset of the CLCD TCO that matches the days on which the ozonesondes were flown and the CLCD worked?

Ans: As mentioned earlier, we compare monthly averages with those from sonde stations located in the same satellite grid box. Upon reviewing our data, particularly for subtropical stations, we found that there were not enough temporally collocated data for reliable validation. Therefore, we decided to rely on temporally non-collocated data to ensure a more robust analysis.

- **221ff:** You show the results for Lindenberg, Uccle, and Payerne. These stations are within 800 km of each other. Thus, I do not have confidence in your statement that “these results

imply that the CLCD method performs consistently across midlatitudes.” This sample is too small and too geographically close together.

Ans: We agree. Rephrased the sentence to “Several central European stations show small mean differences, including Lindenberg (0.0 ± 1.9 DU), Payerne (-0.2 ± 1.8 DU), and Uccle (0.2 ± 2.2 DU) (Fig. 7).”(line number 196-197)

- **225:** Again, “these values highlight the overall reliability of the method.” I do not believe you have provided enough evidence to support this assertion. I am also unclear as to what CLCD product is being validated: daily maps, monthly means, multi-year means?

Ans: The CLCD retrievals are on a daily basis. We validated spatially collocated monthly mean CLCD retrievals against ozonesondes during the period from June 2018 to December 2022. The sentence doesn’t exist anymore due to the updated manuscript.

- **235-236:** “Additionally, CLCD effectively captures seasonal variations in tropospheric ozone across most stations.” Define effectively? The magnitudes of the seasonal cycles of CLCD results shown in Figure 7 look different from the actual data, although given the relatively large uncertainty in the CLCD product, not statistically significantly so...

Ans: Dropped the word “effectively,”. Revised the text to “However at most stations, the seasonal amplitude of the CLCD is slightly larger than that derived from sonde measurements. This shows a tendency for CLCD to marginally overestimate the seasonal cycle. Given the relatively large standard deviation of the monthly CLCD means, these differences are hardly significant (Fig. 7).”
line number (202-204)

- **238:** “...more reliable ozone measurements across diverse atmospheric conditions.” Can you show results for how the dynamic choice between CLCD-C and CLCD-T improved the outcome? What would have happened if you would have stuck with one or the other?

Ans: The dynamic selection between CLCD-C and CLCD-T is designed to adapt the ACCO calculation to different cloud conditions based on cloud-top-height variability. Specifically, CLCD-C is applied under homogeneous cloud conditions, where climatology provides an approximate estimate, while CLCD-T is used in cases of sufficient cloud-top-height variability, where regression-based approaches are more appropriate. An advantage of the CLCD-T method is that it directly retrieves ACCO at the 450 hPa reference level without relying on climatological information.

- **243:** “We conclude no dependencies” in Figure 8. Not sure. The purple dots show some correlation for TOZ, ACCO, and cloud top height, to my eye. Did you run statistical tests on these data or subgroups of data?

Ans: We agree that correlation may be apparent in Fig. 8, however, the large spread and overlap across the variable ranges make it difficult to identify sensible relationships.

Following the reviewer’s suggestion, we performed a statistical analysis to quantify the relationships between CLCD mean bias (MD) to ozone sondes and the relevant ozone and cloud

parameters used in the retrieval.

The high standard deviations make it difficult to identify clear dependencies. For all stations combined, moderate positive correlations are observed between mean bias and both ACCO and clear-sky TOZ ($CF \leq 0.2$) ($r \approx 0.6$) (Figure 8a and b) and a negative correlation with cloud-top-height ($r \approx -0.41$) (Figure 8c).

Other parameters exhibit weaker or inconsistent relationships at the global scale.

For mid-latitude stations, mean bias shows moderate to strong positive correlations with ACCO ($r = 0.71$) and clear-sky TOZ ($r = 0.65$) and a negative correlation with CTH ($r = -0.43$).

For tropical stations, stronger dependencies are found with the ACCO correction to the reference level (the difference between ACCO retrieved and ACCO below 450 hPa level). In particular, mean bias shows moderate negative correlations with the correction term ($r = -0.57$) as well as with cloud-top height (CTH: $r = -0.56$).

Overall, the correlation analysis indicates moderate relationships between CLCD mean bias and selected ozone and cloud parameters. These relationships vary by region, with ACCO and clear-sky TOZ showing the strongest correlations at mid-latitudes, while the ACCO correction and cloud-top height are more associated with mean bias in the tropics.

We updated the text as “Figure 8 shows the relationships between CLCD bias, scatter, and selected ozone and cloud parameters. The high standard deviations of these parameters introduce additional uncertainty, making it more difficult to identify clear dependencies. For all stations combined, moderate positive correlations are observed between mean bias and both ACCO and clear-sky TOZ ($CF \geq 0.2$) ($r \approx 0.6$) (Fig. 8a and b) and a negative correlation with cloud-top-height ($r = -0.41$) (Fig. 8c). Other parameters exhibit weaker or inconsistent relationships at the global scale.”

“For mid-latitude stations, mean bias shows moderate to strong positive correlations with ACCO ($r = 0.71$) and clear-sky TOZ ($r = 0.65$). For tropical stations, stronger dependencies are found with the ACCO correction to the reference level (the difference between ACCO retrieved and ACCO below 450 hPa level). In particular, mean bias shows moderate negative correlations with the correction term ($r = -0.57$) as well as with cloud-top height ($r = -0.56$).”

“Overall, the correlation analysis indicates moderate relationships between CLCD mean bias and selected ozone and cloud parameters. These relationships vary by region, with ACCO and clear-sky TOZ showing the strongest correlations at mid-latitudes, while the ACCO correction and cloud-top height are more associated with mean bias in the tropics” (**Line number 207-219**).

- **268:** “The higher cloud cover...” You mean “greater amount of cloud cover” rather than “higher altitude cloud cover,” correct?

Ans: The sentence doesn't exist due to the update of manuscript.

- **Figure 7:** Seems as though at most sites, the annual cycle has a greater magnitude in the CLCD data than in the sonde data. Does that provide insight into the approach itself? Also,

the caption describes “ozonesonde tropospheric columns above 450 hPa.” Is it below in altitude and above in pressure coordinates?

Ans: Yes. We agree. At most stations, the seasonal amplitude of the CLCD is slightly larger than that derived from sonde measurements. This shows a tendency for CLCD to marginally overestimate the seasonal cycle. However, given the relatively large standard deviation of the monthly CLCD means, these differences are hardly significant.

We rephrased the text in the manuscript as “At remote stations, larger differences are observed. Ascension Island shows a mean difference of -4.2 DU with a standard deviation of 3.7 DU, while Macquarie Island shows $+4.8$ DU with a standard deviation of 2.5 DU. Overall, for stations within 60°S – 60°N , the mean difference is 0.6 ± 2.5 DU. CLCD also captures the seasonal variation in tropospheric ozone at most stations (Fig. 7). At many stations, the seasonal amplitude of the CLCD is slightly larger than that derived from sonde measurements. Given the relatively large standard deviation of the monthly CLCD means, these differences are hardly significant (Fig. 7).” (line number 199-204)

Regarding the caption, “above 450 hPa” refers to pressure coordinates, i.e. the tropospheric ozone column integrated from the surface (1000 hPa) up to the 450 hPa pressure level, which corresponds to below the altitude of this level.

- **Figure 8:** Same comment about directional reference in the figure caption. The caption indicates “ACCO up to 450 hPa.” Does this mean up to in pressure coordinates or up to in altitude coordinates?

Ans: Yes. Here it means up to, in pressure coordinates.

- **272-273:** I gather from these statements that you are applying a climatological correction when the cloud tops are not at 450 hPa. Is that correct? How does this impact comparisons with other TCO products?

Ans: Yes, this is correct. In the CLCD-C method, a climatological correction is applied when cloud-top heights differ from the 450 hPa reference level, adjusting ACCO to ensure a consistent TCO definition. For validation, ozonesonde profiles from SHADOZ, WOUDC, and NDACC are integrated to the same 450 hPa level, ensuring consistency between satellite and in situ data. The uncertainty introduced by this climatological correction is discussed in the manuscript and discussed in subsection climatological correction under Section 5.1.1 (Causes of bias and variability in CLCD-retrievals). Differences with other TCO products may arise if different reference levels or correction methods (or different climatologies) are used; however, within this study, all comparisons are performed consistently at 450 hPa.

- **281-282:** “...the high positive bias in TCO is most likely caused by low-level clouds.” Is this a general statement or something specific to Yarmouth?

Ans: This can be a general cause of overestimating tropospheric ozone when the above-cloud column ozone (ACCO) is underestimated. However, the statement refers specifically to the Yarmouth station.

At Yarmouth, the large positive TCO bias may be associated with the remote cloudy pixels used to estimate ACCO, which may increase the absolute bias due to differences between the ozone columns above the clouds and the local ozone conditions. The positive TCO bias suggests that ACCO may be underestimated. We have revised the sentence as follows:

“Yarmouth similarly has persistent remote clouds, which may contribute to its positive TCO bias, particularly during late winter and early spring (Fig. 9b)” **(line number 239-240).**

- **291ff:** I am having trouble following the arguments in this paragraph.

Ans: We revised the text to a more clearer version as follows; “At Macquarie Island (54.5°S, 158.9°E), the relatively large bias and variability (4.8 ± 2.5 DU) are likely influenced by both enhanced stratospheric ozone variability and remote cloud conditions. Stratosphere–troposphere transport events reported for this region (Greenslade et al., 2017) may produce enhanced ACCO, which can be missed when the selected clouds are distant, potentially leading to underestimated ACCO and overestimated TCO. This is consistent with the larger CLCD–ozonesonde differences during autumn and winter (Fig. 9h). **(Line number 241-245)”**

- **311:** Regarding the ITCZ, the authors state agreement is “likely due to the presence of higher cloud-top-heights.” Can the authors demonstrate this assertion is true?

Ans: As mentioned in the manuscript the statement is supported by the observed cloud-top-height distributions shown in Fig. 12c, which indicate consistently higher cloud-top heights during early boreal summer when the ITCZ is located near the Kings Park station.

- **317-318:** “Costa Rica [shows] both the highest positive bias and the largest correction...” What did co-author Ryan Stauffer have to say about this data set? I believe he is the NASA PI for the station.

Ans: Following the reviewer's comment, we consulted Dr. Ryan Stauffer, who is involved with the Costa Rica ozonesonde record. He noted that the station may be affected by several factors that could influence the tropospheric ozone column derived from ozonesondes.

First, the site is located near active volcanic sources (e.g. Turrialba and Poas), and volcanic SO₂ can interfere with ozonesonde ozone measurements when volcanic plumes are present, potentially leading to a low bias in the sonde derived tropospheric ozone column. While strongly affected profiles can often be identified, weaker SO₂ influences may be more difficult to detect and screen.

Second, previous analyses have identified a change in the Costa Rica ozonesonde tropospheric ozone record beginning around 2016. The origin of this change remains uncertain and may reflect either a real atmospheric signal or an instrumental artifact. Comparisons with satellite products (OMI/MLS) have also indicated this feature. Because of this, Costa Rica was omitted from any TOAR-II trends studies because of the complications with SO₂ interference and the unknown source of a potential ~2016 change in the tropospheric ozone values.

These factors provide an explanation for the relatively large positive bias observed between CLCD and ozonesonde measurements at Costa Rica. However, we retain Costa Rica in the validation

dataset because the objective of the study is to evaluate the retrieval against the available ozonesonde observations, while addressing the known limitations of individual stations.

In the manuscript we now write “The relatively large positive bias between CLCD and ozonesonde measurements at Costa Rica may be related to volcanic SO₂ interference, which can lead to a low bias in sonde-derived tropospheric ozone columns, and an unexplained change in the ozonesonde tropospheric ozone record (Morris et al., 2010; Stauffer et al., 2020). The latter may reflect either a real atmospheric signal or an instrumental artifact and has also been observed in comparisons with satellite products (Ozone Monitoring Instrument/Microwave Limb Sounder)”. **(Line number 266-270)**”

Morris, G. A., Komhyr, W. D., Hirokawa, J., Flynn, J., Lefer, B., Krotkov, N., and Ngan, F.: A balloon sounding technique for measuring SO₂ plumes, *Journal of Atmospheric and Oceanic Technology*, 27, 1318–1330, <https://doi.org/https://doi.org/10.1175/2010JTECHA1436.1>, 2010.

Stauffer, R. M., Thompson, A. M., Kollonige, D. E., Witte, J. C., Tarasick, D. W., Davies, J., Vömel, H., Morris, G. A., Van Malderen, R., Johnson, B. J., et al.: A post-2013 dropoff in total ozone at a third of global ozonesonde stations: Electrochemical concentration cell instrument artifacts?, *Geophysical Research Letters*, 47, e2019GL086791, <https://doi.org/https://doi.org/10.1029/2019GL086791>, 2020.

- **354-355:** In explaining Hanoi, you identify “transport process...likely contributes” and “It is probable that...” Please show some evidence that these are the factors that influenced your results.

Ans: Revised the sentence to “At Hanoi, CLCD-TCO is generally lower than the ozonesonde observations, with the largest differences in early spring and September (Fig. 9e).” **(line number 294-295).**

- **360:** Again, this time for Ascension, “likely tied to biomass burning...” without proof. How can you demonstrate this impact.

Ans: We agree that the link to biomass burning is not directly demonstrated within this study. We intended to refer to previously published research findings. However, we also agree that this explanation requires further evidence and is beyond the scope of this study. Therefore, we have removed this statement and focused the discussion on the comparison between the retrievals and ozonesonde observations.

- **364:** Again for Ascension, “These clouds likely contribute...” Ditto.

Ans: Thank you for this comment. We agree that the previous statement was too speculative. We have revised the text to avoid attributing the bias directly to low-level clouds. Instead, we now emphasize that during late boreal summer and early autumn, Ascension is characterized by a prevalence of limited suitable cloud scenes. This adversely affects the representativeness of the ACCO and reliable validation.

The sentence is now revised to “At Ascension, the largest differences occur during late boreal

summer and early autumn, when suitable cloudy scenes are farther from the station and cloud sampling is limited (Fig. 12). In addition, biomass burning in Southern Africa and South America peaks during this period (Wai et al., 2014), which may increase ACCO and contribute to the negative TCO bias (Fig. 8b and Fig. 10c,d). Thus, the variability at Ascension likely reflects a combination of limited cloud sampling, variable cloud locations, and biomass-burning influence.”
(line number 296-300)

- **375:** “This might explain the high spread during spring in almost all the high latitude NH stations...compared to the SH station.” I am having difficulty looking at the figure and discerning to what the authors are referencing. Also, the NH vortex in winter/spring is often displaced from the pole, causing significant zonal gradients that do not appear as often in the SH where the vortex during winter/spring is usually centered on the pole.

Ans: We agree that the original statement was not clear enough. We have revised the sentence to explicitly clarify that the larger spread refers to increased variability in total ozone and ACCO at the NH stations, as shown in Fig. 9 and Table 1.

This variability may also affect the representativeness of the monthly mean ozonesonde measurements, as a limited number of soundings per month may not adequately capture the ozone variability.

Revised the sentence to “At higher latitudes, larger stratospheric ozone variability can complicate CLCD retrievals despite the applied homogeneity criteria. Total ozone typically peaks during winter and spring because of enhanced transport from tropical source regions (Fahey and Hegglin, 2010; Weber et al., 2011) (Fig. 10). The larger spread observed at the NH stations (e.g., Goose Bay, Yarmouth, and Valentia) compared to the SH station Macquarie Island (Fig. 9 and Table 2) may partly reflect greater ozone variability, which may not be fully captured by the monthly mean ozonesonde measurements when only a few soundings are available (1 to 4 per month) (Line number; 302-307) .

- **380:** “The persistent scatter is consistent across different seasons, indicating substantial variability in stratospheric ozone.” I am not certain that follows logically, even if it is true. Again, please demonstrate.

Ans: We agree that the original statement was too speculative and not sufficiently supported. So we revised the sentence to avoid attributing the persistent scatter to stratospheric variability. Instead, we now refer to previous findings by Tripathi et al. (2010), which show that Valentia is influenced by regional tropospheric ozone variability. Revised the sentence to “Analysis of 2001–2007 data by Tripathi et al. (2010) shows that Valentia receives a relatively large contribution from air masses originating over polluted mainland Europe.”(Line number; 310-311)

Tripathi, O., Jennings, S., O’Dowd, C., Coleman, L., Leinert, S., O’Leary, B., Moran, E., O’Doherty, S., and Spain, T.: Statistical analysis of eight surface ozone measurement series for various sites in Ireland, *Journal of Geophysical Research: Atmospheres*, 115, <https://doi.org/10.1029/2010JD014040>, 2010.

- **384-385:** For King's Park, "This suggests substantial ozone transport...resulting from stratospheric intrusions and biomass burning..." Could be. Please show some evidence.

Ans: The statement is based on the findings of Liao et al. (2021), who report that enhanced ozone levels at King's Park are influenced by transport from mid-latitudes, including contributions from stratospheric intrusions and biomass burning. However, we agree that this explanation requires further evidence and is beyond the scope of this study. Therefore, we have removed this statement and focused the discussion on the comparison between the retrievals and ozonesonde observations

citation: Liao, Z., Ling, Z., Gao, M., Sun, J., Zhao, W., Ma, P., Quan, J., and Fan, S.: Tropospheric ozone variability over Hong Kong based on recent 20 years (2000–2019) ozonesonde observation, *Journal of Geophysical Research: Atmospheres*, 126, e2020JD033 054, <https://doi.org/10.1029/2020JD033054>, 2021.

- **517:** "Despite low NO₂ concentrations, elevated tropospheric ozone levels..." The boundary layer ozone chemistry is complex and non-linear: moving from a NO_x limited to a hydrocarbon limited environment changes the production/loss balance. Furthermore, while NO₂ may well be mainly confined to the boundary layer in these satellite retrievals, O₃ is probably not. I would hesitate to assign high TCO with high surface concentrations, or assign low NO₂ with high TCO as indicating long-range, free-tropospheric transport without surface measurements. I realize you are citing other studies that have looked at this more carefully, but I am not sure why this is in your paper. I find myself unconvinced by any of the "Selected applications" of section 6.

Ans: We agree that the relationship between NO₂ and ozone is complex and non-linear, and that satellite column observations alone cannot be used to directly assume boundary-layer chemistry or long range transport processes. Our intention in this section was only to highlight regions where elevated tropospheric ozone coincides with known emission regions or areas previously identified in the literature. To avoid over interpretation, we have revised the text to remove causal statements linking NO₂ levels directly to ozone production or long range transport.

revised text : "Elevated NO₂ concentrations are evident over the Northeast China Plain (NCP), particularly around Beijing (39.9° N, 116.4° E), where enhanced tropospheric ozone is also observed. High summertime surface ozone levels over the NCP have been widely reported and are associated with strong anthropogenic NO_x emissions and regional photochemical activity (Lu et al., 2018; Gaudel et al., 2018; Lu et al., 2021). In contrast, some northern regions show relatively low NO₂ but elevated tropospheric ozone columns, which may reflect contributions from transport or ozone produced elsewhere in the troposphere (Zheng et al., 2021) **(line number 434-438).**"
Changed the title from selected applications to Selected example maps **(line number 426).**

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