Responses to reviewers

Reviewer 1: Comments---

Specific comments

C1 *This manuscript needs a substantial revision to clearly convey the similarities and differences among the presented algorithms. The four algorithms involved in this work is 4.1 CPC algorithm, 4.2 CLC algorithm, 4.3 CLCT algorithm as well as the standard CCD algorithm (3.2). The algorithm descriptions span from pages 5 to 11, including an extensive repetition of common processes shared across each algorithm. Moreover, it is inappropriate to treat them as independent algorithms for CPC, CLC, and CLCT, respectively, they should be specific option details in the process of the reference sector choice (pacific or local) and the adjustment schemes (climatological, regression).*

Revised: We have addressed repetitions and refined the text (**Section 4**).

C2 Revise the structures. My suggestion is

1. *data*
- *TROPOMI (bring here 2.1 and introduce the TROPOMI total ozone/cloud/CCD TCO products)*
- *ozonesonde*
- *Algorithms*

First describe the general common process. And then specify implementation details in each section.

- *standard CCD*
- *Authors' algorithm*

4 results

Revised: We changed the structure and modified the text. We would still like to keep the description of the CCD TCO product after the description of our algorithms so that we can shorten it by only highlighting the differences with CPC (**l 200-209**).

C3 5.1 ***Uncertainty Budget***. *The error budget estimation method needs to be improved. According to Equation 1, the uncertainty estimate is almost dependent on the number of samplings for each grid box. But, In the local reference sector process, the longitudinal range of the reference sector is expanded until the minimum of sampling encounters, affecting the inhomogeneity of the samplings. The error term to the inhomogeneity of the samplings caused by stratospheric variability and upwelling of the boundary layer into the upper troposphere, should be included.*

Revised: Added two more terms to the equation: the standard deviation from averaging total ozone under clear sky conditions and the above-cloud column ozone (stratospheric ozone) (**Section 5.1**). Equation 1, Figure 7, and the corresponding text have been modified accordingly.

C4. Section 5.2 *should be significantly revised. It is not proper to deliver comparison results for each station. My suggestion is to discuss the validation results, separately w.r.t 1) geophysical variables (e.g. total column ozone, cloud pressure, aerosol index) using all pairs from all stations (not each station) 2) seasonal comparison for maybe several sectors (e.g., pacific region, subtropical), 3) Figure 12 and Table 1 and a few stations from Figure 8 to summary the validation results.*

Revised : Seasonal comparisons with ozonesondes have been conducted across several sectors (Pacific, Non-Pacific, and subtropical) (**Section 5.2.1)**. The summary and validation results, along with updated figures, have been included. We have retained the station-by-station analysis, as the other reviewer has expressed interest in this aspect.

C5. *It is more interesting to see the comparison/evaluation results for ACCO with each meteorology against ozone sonde, rather than TCO.*

Revised : We have added an additional figure (**Figure 14**) that presents mean differences and standard deviations between TROPOMI and sonde measurements versus the average ACCO corrections at the 270 hPa reference level for all three CHORA algorithms and each station and discussed the results (**Section 5.3.3**).

Reviewer 2: Comments---

Major comments

As far as I understood the CHORA data are provided on a daily basis. To me it is not clear whether the validation is performed on a daily or monthly basis:
***l127**: "Ozonesonde profiles are considered collocated to the satellite data when the station is inside the spatio-temporal grid-box of the TROPOMI tropospheric ozone data, here 0.5° x 0.5° and the same day". (daily comparison)*
***l246**: "The monthly mean of tropospheric ozone retrievals ... from all three CHORA algorithms were calculated." (sounds like monthly data)*

Ans: Here we intended to say spatially collocated. Changed the sentence to "Ozonesonde profiles are considered spatially collocated to the satellite data when the station is inside the grid-box of the TROPOMI tropospheric ozone data, here 0.5◦ × 0.5◦" We provide daily data, but validations are conducted using monthly averages.

***Despite the first statement** it seems to be on a monthly average: To a large extent the deviations in the subtropics are driven by the March soundings in Hanoi. As one explanation the authors mention "The challenge of limited ozonesonde measurements* *in March further complicates the validation." (L274) You would need at least 15-20 measurements per month to represent the monthly mean values adequately. This is not given at any sounding station. Because of that I recommend comparison on a daily basis.*

Ans: From June 2018 to December 2022, Hanoi has only 4 ozonesonde measurements in March which is too sparse to compare.

We appreciate your suggestion, but upon reviewing our data, particularly for subtropical stations, we noticed a lack of sufficient daily collocated data for validation Therefore, we chose to rely on non-collocated data to ensure a more robust analysis. It's important to note that our daily TCO retrievals do not involve any smoothing. Seasonal variation of TCO with daily collocated data is shown in the supplement (Fig.S1).

The description of the *CPC algorithm (fixed pacific reference) states that it is designed for the 20°S to 20°N latitude band. However, throughout the manuscript it is applied from 25°S to 25°N and beyond e.g. figure 8 (comparison to Irene 25.9°S). When looking at the operational CCD dataset, the data in the "winter hemisphere" are often corrupted due to the lack of convective clouds outside the 15° range. Here some more details should be added how the respective extension is achieved.*

Ans: Our aim was to assess the performance of the CPC algorithm in extending it to the subtropics and compare it with local cloud algorithms. While the CPC algorithm follows the same methodology as the operational TROPOMI Level 2 product, it differs primarily in the threshold for cloud fraction (CF $\leq$ 0.2) used to select non-cloudy scenes, the number of days averaged, climatology, and grid resolution. However, we have chosen not to validate CPC beyond 20° latitude. The figures and text have been updated accordingly.

Minor comments

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l 124*: "and when the burst height of the sonde is below 15 km." replace the "and" by "or"? what is the reason for the second requirement? Of cause, if the burst height is below the 270 hPa altitude level the data are not useful but it does not matter the balloon bursts at 14.8 km*

Revised: replaced "and" by "or"
The sonde column is not processed when data gaps in the profiles are wider than 1.2 km or when the burst height of the sonde is below 15 km.

p 5*: The authors should decide whether the column between the surface and 270hPa is above (caption figure1) or below (l134) this pressure levels. From my point of view both have their justification: "above" (because the pressure gets higher) or "below" as* *the altitude is below the 270hPa level, but using both (within a few lines) is a bit confusing.*

Revised: Replaced "below" by "above" for the caption of Figure 1. The other sentence (**earlier l 134**) doesn't exist anymore after updating the text.

l 151: *The product readme file recommends a qa-value greater than 70 (refrence ESA_21b, https://sentinel.esa.int/documents/d/sentinel/s5p-mpc-dlr-prf-o3_tcl_v02-06-01_2-7_20231129_signed). This will probably not improve the validation with sondes.*

Revised: We followed the variable description in the ESA operational data file, which states that the "qa_value is a continuous quality descriptor, varying between 0 (no data) and 1 (full quality data). It is recommended to ignore data with qa_value < 0.5."

We recalculated the data using a qa-value threshold of greater than 0.7 and updated the figures (Figures 8 to 11 and 16) and the numbers in Table 1 accordingly.

p5 and 6 *I suggest to combine the descriptions of the operational ESA product and the CPC. The algorithm is basically the same except for the climatology and the daily vs 3 day averages.*

Revised: Modified the text. We explained the CCD algorithm in general and clarified that while CPC and the ESA product use the same methodology, they differ in terms of climatology, averaging, and grid resolution (**l 200-209, Section 4.4**).

l 165 *The CPC algorithm is described as being applied between 20°S and 20°N, but in Figure 13 data up to 25° South and North are shown (see also major comments).*

Revised: As mentioned earlier, the validations for CPC beyond 20° are omitted and updated the figures and text accordingly.

l 216: *This sentence is unclear:" ... by substituting the values of slope and medians of the ACCO ..."by what? and why replacing the median of the ACCO?*

Revised: Replaced "substituting" with "applying". The Theil-Sen estimate of the intercept can be obtained from the linear regression of ACCO against cloud top pressure (now **l 191**)

figure 6: *"latitude band 2.4° S - 0.4° S and longitude band 26.8° E - 46.8° E" according to the previous description I expected a latitude range of ± 1° for a grid box of 0.5°, so 1.25 °S +1° = 0.25°S to 2.25° S but not 2.4°. The same holds for the longitudinal range. I assumed the centre of the grid box to be the respective starting point.*
How fast are the longitudinal ranges extended. Starting with ±5°, what is the next step if the number of cloudy data is too low, ±10°?

Revised: Updated the figure and the latitude and longitude range. Yes. Regarding the longitudinal expansion the next step would be ±10°, with an increment of ±5°.

l245 *I suggest to look for additional sonde data at* https://woudc.org/data/explore.php?lang=en *especially for the subtropical areas (Hong Kong "King's Park")*

Revised: Validated the results with ozone sonde data over King's Park. Updated Table 1 and all figures (Figures 8 to 16) accordingly.

l 271 *as well as in many other places (figures 10 and 11) throughout the manuscript, the seasons are revered to as Spring to Winter, according to our northern hemispheric seasons. I am not sure if this useful in the tropical to subtropical regions. I suggest to use the month instead, or local dry and wet season.*

Revised: We have updated the seasons in the text using boreal and austral terminology. The months corresponding to each season are specified in the figure captions (Figures 12 and 13).

Figures 8 and 9 *Can you include the operational O3_TCL product in this figures? It is included in figure 13 so the analysis has already been done anyway.*

Revised: We added the operational O3_TCL product (called CCD-ESA in the paper) to Figs. 8,9,10,11, and S1.

figure 10*: this is a very interesting figure - maybe you could make more use of it? For example, the median distance of deep convective clouds over Ascension Island is (3000km) more or less independent of the season. That means the deep convective clouds are over the South American continent.*

Revised: Figure 12 has been updated. Additionally, the station-by-station analysis for Ascension Island has been revised (**l 375 to l 388**).

Figure 11*: include the 270 hPa level in the figure*

Revised: Included and updated the caption of the figure (now labelled as Figure 13) accordingly.

Discussion of individual sounding stations.
For some stations it might be nice to have figure of the differences per month, however including this in the manuscript might extend it too much. How about adding such figures to a supplement?

Revised: We value your suggestion. We think the figure (Fig.11) is important for displaying the seasonal variations in terms of differences and supporting the validation process. To maintain clarity and provide important insights, we have decided to keep the figure in the main text.

***l 315ff** (Paramaribo) How about local sources, biomass burning might also occur in the vicinity of Paramaribo?*

Ans: According to Peters et al. (2004), during the dry season (Aug- Nov) the amount, frequency, and timing of ozone pollution events at Paramaribo depend mostly on the occurrence and intensity of fires over Africa, the lofting of plumes to the free troposphere by convection, and subsequent transport by the tropical easterlies. The transport of biomass-burning plumes from South America itself is less frequent in this period.

***l 343-346** (Kuala Lumpur) The CPC compares better to the sondes than the local cloud reference algorithms. Does this imply that for the local reference algorithms the reference area might be too small and should be increased by default. How large are the local reference areas for a typical dry and wet season? According to figure 10 the mean distance is very small (~200km) only for the Nov-January region the distance is slightly larger.*

Ans: As mentioned in the paper, even though the local cloud reference sector used in both CLC and CLCT algorithms belongs to the Pacific sector, the fixed large Pacific cloud reference sector ensures the inclusion of more high-reflective clouds and a comparatively less polluted background, which benefit the CPC retrievals over Kuala Lumpur. The local reference areas are selected automatically whenever more than 50 cloudy scenes are found, which is the case for Kuala Lumpur. Increasing the local reference area too much by default would reduce the sensitivity of ACCO measurements.

The Figure of cloud distances from the station (Figure 12) is now updated.

***Figure 13**: maybe a longitudinal plot might be more telling. The fixed reference region algorithms (CCD-ESA and CPC) compare best to the sondes in the reference region (70°E to 170°W, Fiji, Samoa and Kuala Lumpur), outside the reference region the CLC algorithms might show their capabilities.*

Ans: Even though Fiji and Samoa are in the fixed Pacific reference sector, local cloud algorithms show similar or better agreement with ozonesondes compared to the CPC and CCD-ESA algorithms. Only over Kuala Lumpur do the CPC and CCD-ESA algorithms show better agreement.

***l 481**: this sensitivity study might be interesting, parts of it might be shown in a supplement.*

Ans: The sensitivity study was conducted using non-gridded data. Unfortunately, I am unable to include this in the supplement at this time.

l 500 *shift figure 13 to here.*

Ans: Shifted Figure 13 (now Figure 16) to the end of the sentence. Changed the sentence to, "The operational TROPOMI tropospheric ozone data (CCD-ESA) consistently exhibit a positive bias across all ozonesonde stations, which is maximum among all satellite datasets (Fig.16) (now **l 542**).

Technical comments

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l 58 *"... in the time frame of 2017 -2022" even if this was the original plan, meanwhile it's 2024 S5P is still operational and we get very nice results every day. I suggest to replace by " ...the timeframe after 2018"*

Revised: Changed accordingly. "…providing information and services on air quality, climate forcing, and ozone layer in the time frame after 2018."

l 84/85 *"3.5 x 7.5 km² (across-track x along-track), was further refined to 5.5 x 3.5 km²". exchange the updated resolution to 3.5 x 5.5 km² to have across-track x along-track.*

Revised: Changed accordingly. "…, originally of 3.5×7 km², was further refined to 5.5×3.5 km² (across-track × along-track) on 6 August 2019."

l 475 *"significantly small", what does this mean? significant or small or significant but small?*

Revised: That exact sentence doesn't exist anymore after updating the text. (**l 487-489**)

Comments by Owen R. Cooper (TOAR Scientific Coordinator of the Community Special Issue) on: --

Improved CCD tropospheric ozone from S5P TROPOMI satellite data using local cloud fields

Swathi Maratt Satheesan, Kai-Uwe Eichmann, John P. Burrows, Mark Weber, Ryan Stauffer, Anne M. Thompson, and Debra Kollonige

EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-2825, 2024
Discussion started: 23 Feb 2024; Discussion closes March 29, 2024

This review is by Owen Cooper, TOAR Scientific Coordinator of the TOAR-II Community Special Issue. I, or a member of the TOAR-II Steering Committee, will post comments on all papers submitted to the TOAR-II Community Special Issue, which is an inter-journal special issue accommodating submissions to six Copernicus journals: ACP (lead journal), AMT, GMD, ESSD, ASCMO and BG. The primary purpose of these reviews is to identify any discrepancies across the TOAR-II submissions, and to allow the author teams time to address the discrepancies. Additional comments may be included with the reviews. While O. Cooper and members of the TOAR Steering Committee may post open comments on papers submitted to the TOAR-II Community Special Issue, they are not involved with the decision to accept or reject a paper for publication, which is entirely handled by the journal's editorial team.

General Comments:

TOAR-II has produced two guidance documents to help authors develop their manuscripts so that results can be consistently compared across the wide range of studies that will be written for the TOAR- II Community Special Issue. Both guidance documents can be found on the TOAR-II webpage: https://igacproject.org/activities/TOAR/TOAR-II

The TOAR-II Community Special Issue Guidelines: In the spirit of collaboration and to allow TOAR-II findings to be directly comparable across publications, the TOAR-II Steering Committee has issued this set of guidelines regarding style, units, plotting scales, regional and tropospheric column comparisons, tropopause definitions and best statistical practices.

Guidance note on best statistical for TOAR analyses: The aim of this guidance note is to provide recommendations on best statistical practices and to ensure consistent communication of statistical analysis and associated uncertainty across TOAR publications. The scope includes approaches for reporting trends, a discussion of strengths and weaknesses of commonly used techniques, and calibrated language for the communication of uncertainty. Table 3 of the TOAR-II statistical guidelines provides calibrated language for describing trends and uncertainty, similar to the approach of IPCC, which allows trends to be discussed without having to use the problematic expression, "statistically significant".

Major Comments:

This manuscript describes the new CHORA (Cloud Height Ozone Reference Algorithm) algorithm for retrieving tropospheric ozone columns from TROPOMI, which improves upon the standard CCD (Convective Cloud Differential) approach that uses cloud data from the Pacific region. The topic is relevant to TOAR-II and the product will be useful to the scientific community. I see no discrepancies between this paper and the other papers that have been submitted to the TOAR-II Community Special Issue so far. I have a few suggestions to improve the description of the method, and to cite relevant work from TOAR and other research groups, as follows:

The region of the subtropics does not have a clear definition. According to the AMS Glossary of Meteorology (https://glossary.ametsoc.org/wiki/Subtropics) the subtropics is vaguely defined as: "The indefinite belts in each hemisphere between the regions of tropical and temperate climates." It would be helpful if the Methods section can define your interpretation of the latitude bounds of the tropics, subtropics and mid-latitudes. It seems that you are using 20 degrees as the boundary of the tropics and subtropics. It also seems that you are classifying Hilo as tropical even though it is very close to the latitude of Hanoi, and even though it is impacted by mid-latitude air masses (and stratospheric intrusions) like the other subtropical cites. Is there a compelling reason to treat Hilo separately from the subtropical sites?

Ans: The standard CCD method is formulated for the tropics, covering within 20 degrees north and south of the equator (20S–20N). While Hilo is near the subtropics and can indeed be influenced by mid-latitude air masses and stratospheric intrusions, it still falls within this tropical boundary. Therefore, we have classified Hilo within the tropical region in accordance with the methodology established for the CCD approach (Leventidou et al. 2018, Hubert et al. 2021).

In several places the paper discusses the potential impact of stratospheric intrusions in the tropics, but provides few citations that describe this process. Nice overviews of the location and frequency of stratospheric intrusions are provided by Škerlak et al. (2014) and Škerlak et al. (2015). In terms of intrusions directly impacting the Hilo ozonesonde station (located near Mauna Loa Observatory), the first study to show that stratospheric ozone can impact Mauna Loa was Hübler et al. (1992); other studies are Cooper et al. (2005) and Lin et al. (2014).

Revised: Updated the references. (**line 36, line 259**)

Introduction
When summarizing global tropospheric ozone trends, a concise summary can be found in Chapter 2 (Section 2.2.5.3) of IPCC AR6 (Gulev et al, 2021). The earliest known free tropospheric ozone observations (mid-20th century) are reviewed by Tarasick and Galbally et al. 2019 (a paper from the first phase of TOAR), which were lower than the present-day, although the data coverage was very limited.

Dr. Klaus-Peter Heue posted an open comment on this paper and pointed out that 15-20 ozone profiles per month are required to produce an accurate monthly mean. This number was established by earlier work published by Logan (1999) and Saunois et al. (2012), which focused on mid-latitudes. A new study submitted to the TOAR-II Community Special Issue shows similar results for the tropics by focusing on free-tropospheric ozone measured at Mauna Loa Observatory (Chang et al., 2024).

Ans: We appreciate your suggestion, but upon reviewing our data, particularly for subtropical stations, we noticed a lack of sufficient daily collocated data for validation (seasonal variation of Tropospheric Column Ozone (TCO) with daily collocated data is shown in the supplement for reference (Fig.S1). Therefore, we decided to rely on non-collocated data to ensure a more robust analysis. It's important to note that our daily TCO retrievals do not involve any smoothing.

Minor Comments:

line 32
smog is not a scientific term and should be replaced by something like air quality

Revised: Changed the sentence (**now line 30**) as;

“At the top of the troposphere, it acts as a greenhouse gas and contributes to global warming. When it appears closer to the earth’s surface, it adversely affects the air quality and is hazardous to the health of humans, animals, and vegetation”.

line 32
Regarding the potential impacts of ozone on animals, it seems likely that animals would be affected, but I don’t know of any studies that have ever demonstrated this link. Can you find an authoritative reference?

Revised: Added new references (Crutzen, 2016; Iriti and Faoro, 2008; Fleming et al., 2018; Mills et al., 2018; Gaudel et al., 2018; Szopa et al., 2021) to the sentence (**line 32**).

line 32
While Paul Crutzen made key contributions to the field of ozone research, his description of the Anthropocene is not a good reference for the impact of ozone on human health, vegetation, or climate. It would be more appropriate to cite IPCC and the TOAR-I papers (Fleming and Doherty et al., 2018; Mills et al., 2018; Gaudel et al., 2018; Szopa et al., 2021).

Revised: Added the above-mentioned references (**line 32**).

line 46
change lifespan to lifetime

Revised: Changed to lifetime (**now line 46**).

“However, due to its short lifetime and dependence on sunlight and precursor emissions from natural and anthropogenic sources, tropospheric ozone exhibits a high spatio-temporal variability on seasonal, interannual and decadal time scales

(Cooper et al., 2014b; Putero et al., 2023; Seguel et al., 2024) which, in turn, poses a clear challenge to the satellite observing system”

line 46-49

The purpose of this sentence is to demonstrate that tropospheric ozone’s high spatial and temporal variability poses a challenge to satellite monitoring. I don’t understand how the paper by Kgabi and Sehlolo (2012) is relevant. This paper does not seem to be indexed with Web of Science, although I could find it through Google Scholar. It focuses on urban ozone in Johannesburg, and one nearby rural site, so it does not provide any kind of broad regional or global overview. Again, the TOAR-I papers would be very appropriate, and there are new papers submitted to the TOAR-II Community Special Issue that also provide large-scale regional and continental surveys, such as Putero et al., 2023, and Seguel et al., 2024.

Revised: Removed the reference Kgabi and Sehlolo (2012) and updated by adding the above-mentioned references. (**Now line 48**)

line 159

the word “before” is not necessary

Revised: That sentence doesn’t exist anymore due to the updated text.

line 261

A paper that looks at ozone increases over Hanoi is Ogino et al., 2022. Another recent paper that looks at ozone increases about Southeast Asia is Li et al., 2023.

Revised: updated the reference for Hanoi (**now line 416**).

References:

Leventidou, E., Weber, M., Eichmann, K.-U., Burrows, J. P., Heue, K.-P., Thompson, A. M., and Johnson, B. J.: Harmonisation and trends of 20-year tropical tropospheric ozone data, Atmospheric Chemistry and Physics, 18, 9189–9205, 2018.

Hubert, D., Heue, K.-P., Lambert, J.-C., Verhoelst, T., Allaart, M., Compernolle, S., Cullis, P. D., Dehn, A., Félix, C., Johnson, B. J., et al.: TROPOMI tropospheric ozone column data: geophysical assessment and comparison to ozonesondes, GOME-2B and OMI, Atmospheric Measurement Techniques, 14, 7405–7433, 2021.