

- **RC2:**

## **Review of “Extension of the S5P-TROPOMI CCD tropospheric ozone retrieval to mid-latitudes,” by Maratt Satheesan et al. 2025**

Maratt Satheesan et al. present a new satellite algorithm to retrieve tropospheric column ozone (TCO) defined as surface–450 hPa from S5P/TROPOMI across 60° S–60° N. The method selects a local cloud reference sector (radius adaptively grown from ~60 to 600 km) to estimate above-cloud column ozone (ACCO) locally, adjusts ACCO to a common upper layer (450 hPa), and then derives grid-box TCO for nearby clear pixels by subtracting this ACCO from the total column. The algorithm operates in two modes: CLCD-C (climatology-based) and CLCD-T (Theil–Sen regression using cloud-top variability). Monthly TCO fields for 2018–2022 on a 0.5°×0.5° grid are validated against 36 ozonesonde sites, with an overall mean bias of about 0.6 DU and dispersion of about 2.5 DU reported. The resulting TCO product could be useful for trace-gas studies.

### **Major comments**

**1.** The manuscript is dense. Please consider shortening background and moving secondary figures to SI to focus the main text on algorithm, validation, and key findings.

**Ans)** We have shortened the introduction, Section 5 (Validation), and discussions.

### **2. Product definition and comparability**

Please consolidate the product definition in a single table: vertical layer (surface–450 hPa), grid (0.5°×0.5°), temporal averaging (daily box means → monthly composites), and coverage. Include a side-by-side comparison with existing TCO products—e.g., TROPOMI O3\_TCL (surface–270 hPa), OMI/MLS (surface–tropopause), and one reanalysis—highlighting differences in layer definitions, resolution, and known biases. Provide diagnostic maps of (surface–450 hPa) – (surface–tropopause) and (surface–450 hPa) – (surface–270 hPa) so users can reconcile your product with traditional TCO definitions.

**Ans)** We have added a summary table describing the main characteristics of the CLCD-TCO product, including the vertical integration range (surface–450 hPa), spatial resolution (0.5° × 0.5°), temporal resolution (daily retrievals aggregated to monthly means for validation and analysis), and the data coverage period (2018–2022). Please find the following table **(Line number 154)**

| Parameter                          | CLCD-TCO product definition                                                                                          |
|------------------------------------|----------------------------------------------------------------------------------------------------------------------|
| Product quantity                   | Tropospheric column ozone (TCO)                                                                                      |
| Vertical integration range         | Surface to 450 hPa                                                                                                   |
| Retrieval approach                 | Convective Cloud Differential (CCD) technique using local cloud reference sectors (CLCD)                             |
| Input data                         | TROPOMI total ozone and cloud parameters (OCRA/ROCINN)                                                               |
| Spatial resolution                 | 0.5° × 0.5° latitude–longitude grid                                                                                  |
| Temporal resolution                | Daily retrievals; monthly averages used for validation and analysis                                                  |
| Data coverage                      | 2018–2022                                                                                                            |
| Cloud reference sector             | Adaptive local circular sector (radius range; 60 - 600 km), expanded based on cloud availability for ACCO retrievals |
| Minimum cloud sampling requirement | At least 20 valid ACCO measurements within the cloud reference                                                       |
| ACCO calculation                   | Mean ACCO determined using Theil–Sen regression (CLCD-T) or climatological correction (CLCD-C)                       |
| Validation dataset                 | ozonesondes from SHADOZ, WOUDC, and NDACC networks                                                                   |

Our work focuses on the development and validation of the CLCD retrieval using TROPOMI total ozone observations and ozonesonde measurements, and does not make use of TROPOMI O3\_TCL, OMI/MLS, or reanalysis datasets. Therefore, we believe that incorporating these additional products would not directly support the primary goals of this study

### 3. Algorithm transparency & reproducibility

**(a)** Document the local cloud sector growth (start radius, increment, stop criteria, near-overcast thresholds) and whether pixels are area- or quality-weighted. Provide a sensitivity study for sector radius caps (60/300/600 km) on ACCO stability.

**Ans)** We thank the reviewer for this suggestion. We have clarified the description of the local cloud reference sector selection in the revised manuscript.

The cloud reference sector is initially defined with a radius of 60 km around the center of each 0.5° × 0.5° retrieval grid box. The radius is then increased iteratively in steps of 60 km up to a possible maximum radius of 600 km. Iteration stops when at least 20 cloudy ground pixels (cloud fraction ≥ 0.8 and cloud-top height > 2 km) are available for calculating ACCO. If this criterion is not met at the maximum radius, no retrieval is performed and a fill value is assigned. All cloudy pixels contributing to ACCO are equally weighted.

We tested smaller maximum radius limits (e.g., below 600 km) and found that they frequently resulted in insufficient cloudy pixel sampling. Therefore, a maximum radius of 600 km was selected as a practical upper limit to ensure sufficient ACCO sampling while maintaining a localized

reference sector. Since the algorithm selects the smallest radius that satisfies the cloudy pixel requirement, the maximum radius is only reached in cases with limited cloud availability.

We updated the text as follows: “The circular cloud reference sector is initially defined with a radius of 60 km around the center of each  $0.5^\circ \times 0.5^\circ$  retrieval grid box. The radius is then increased iteratively in steps of 60 km up to a possible maximum radius of 600 km. Iteration stops when at least 20 cloudy ground pixels (cloud fraction  $\geq 0.8$  and cloud-top height  $> 2$  km) are available for calculating ACCO (Fig.2). If this criterion is not met at the maximum radius, no retrieval is performed and a fill value is assigned. All cloudy pixels contributing to ACCO are equally weighted. We tested smaller maximum radius limits (e.g., below 600 km) and found that they frequently resulted in insufficient cloudy pixel sampling. Therefore, a maximum radius of 600 km was selected as a practical upper limit to ensure sufficient ACCO sampling while maintaining a localized reference sector. Since the algorithm selects the smallest radius that satisfies the cloudy pixel requirement, the maximum radius is only reached in cases with limited cloud availability.”  
**(Line number 116-124).**

**(b)** Please justify representativeness when sectors exceed several degrees in longitude/latitude (e.g., at  $60^\circ$  N, 600 km is about  $10^\circ$  of longitude). Terrain-stratified validation (plains vs mountains) would help quantify impacts over complex topography.

**Ans)** We agree that large reference sectors may reduce spatial representativeness, particularly at higher latitudes where a 600 km radius can span several degrees in longitude. However, the maximum radius is only reached when smaller sectors do not provide sufficient cloudy pixels for ACCO calculation. The algorithm always selects the smallest possible sector that satisfies the sampling requirement (minimum of 20 cloudy pixels), thereby minimizing the spatial extent of the reference region.

The validation includes stations located at different altitudes. Based on the station-to-station comparison, we do not observe an obvious systematic dependence of the CLCD-TCO bias on terrain height. The larger differences observed at some stations do not appear to be consistently associated with complex terrain and appear to be influenced by other factors, including clouds and ozone .

**(c)** Specify all homogeneity criteria for total ozone and report rejection rates. Clarify time mapping: is ACCO derived and applied to clear pixels within the same orbit/day, or via compositing? Also state the ozonesonde measurement time and the collocation time window relative to the S5P overpass.

**Ans)** The CLCD retrieval applies two homogeneity criteria. First, the reference sector for the cloudy scenes is screened based on total ozone variability: the standard deviation ( $1\sigma$ ) of total ozone under cloudy condition (cloud fraction  $\geq 0.8$ ) within the selected local cloud sector must be less than 10 DU. This criterion removes cases where strong spatial gradients in stratospheric ozone may affect the ACCO estimation. Second, ACCO retrievals are only performed when the local cloud sector contains at least 20 cloudy ground pixels with cloud fraction  $\geq 0.8$  and cloud-top height  $> 2$  km. If either criterion is not fulfilled, the retrieval is assigned a fill value and quality flag 5.

The rejection rate based on the total ozone inhomogeneity is generally low and ranges from **0 to 4%**, with most stations being below **3%**. No rejections due to this criterion occur at several tropical and subtropical stations. Overall, this filtering removes only a small fraction of the available retrievals. For validation with ozonesondes, the monthly means of TROPOMI measurements are compared with corresponding monthly means of ozonesonde measurements.

**(d)** Provide per-region CLCD-C vs CLCD-T usage fractions through the year.

**Ans)** The CLCD-C and CLCD-T usages were analysed in the tropical, subtropical, and midlatitude regions CLCD-C accounts for about 80% of the retrievals at midlatitudes, while CLCD-T accounts for about 20%. In the subtropical region, the two methods contribute more equally, with CLCD-C accounting for 57% and CLCD-T for 43% of the retrievals. In the tropics, the usage is nearly evenly split, with CLCD-C accounting for 49% and CLCD-T for 51%.

Overall, CLCD-C is the dominant approach at midlatitudes, whereas the tropical region shows nearly equal usage of both methods. The subtropical region lies between these.

#### **4. Cloud distance & 3D cloud radiative effects**

Define distance-to-cloud-edge formally (measurement space, units, how edges are detected). In Fig. 6f the mean distance spans from 50 to more than 400 km; please explain this range and any sharp transitions. Quantify the CLCD-TCO residuals vs edge distance diagnostics to reveal 3D effects. Clarify handling of cirrus and multi-layer clouds and their impact on effective cloud pressure.

**Ans)** We would like to clarify that the cloud distance parameter shown in Fig. 6f does not represent distance to the cloud edge. It represents the mean distance between the retrieval location (center of the  $0.5^\circ \times 0.5^\circ$  grid box) and the cloudy pixels used within the selected local cloud reference sector.

Therefore, smaller values indicate that the ACCO estimation is based on nearby local clouds, whereas larger values indicate that more distant clouds are required to fulfil the minimum cloudy pixel requirement. Regions with sufficient nearby clouds have smaller mean distances, while regions with sparse cloud coverage require expansion of the reference sector and inclusion of more distant clouds.

Regarding cloud type, the current CLCD implementation does not explicitly use multi-layer cloud scenes or quantify their impact. The approach relies on the TROPOMI cloud-top-height (cloud-as-a-reflecting-boundary) and cloud fraction data (Loyola and Ruppert, 1998; Rodriguez et al., 2007)

#### **5. Uncertainty**

Report relative as well as absolute uncertainty, and decompose errors into random and systematic terms. Provide the frequency of negative ACCO/TCO, and guidance on QC thresholds to achieve typical targets (e.g.,  $\leq 10\%$  relative error for monthly  $0.5^\circ$  boxes). Please discuss error correlation within sectors (shared ACCO) and implications for averaging.

**Ans)** We thank the reviewer for this suggestion. We have done the uncertainty analysis by using Eq. (1) (**Line number 158**).

The uncertainty in Eq. (1) is calculated independently of the ozonesonde measurements. The first two terms represent the random retrieval uncertainties of TOZ and ACCO, which decrease with the number of measurements. The uncertainties associated with cloud fraction and cloud-top height are propagated uncertainties. The standard deviations of the clear sky TOZ and ACCO represent the variability of these quantities within the corresponding sampling regions.

The uncertainty estimated from Eq.(1) is approximately 4 DU on a 5-year average of the daily uncertainties for June and December (2018–2022). For comparison, the independent validation gives a mean CLCD-TCO minus ozonesonde difference of 0.6 DU and a standard deviation of 2.5 DU. The small mean bias indicates that the systematic difference between CLCD-TCO and the ozonesonde measurements is relatively small compared with the estimated uncertainty. The 2.5 DU standard deviation is also smaller than, the estimated daily uncertainty of approximately 4 DU. The difference is expected because the uncertainty from Eq. (1) represents daily retrieval uncertainty, whereas the validation statistics are based on monthly mean spatially collocated satellite and ozonesonde measurements and therefore include the effects of temporal and spatial averaging as well as sampling differences.

As described in the response to **P6 I-165** (see further down), we assign quality flag 5 when the retrieved TCO becomes negative. A negative TCO occurs when the retrieved ACCO is larger than the total ozone column (TOZ), since TCO is calculated as the difference between clear sky TOZ and ACCO. 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.

Individual CLCD retrievals within a grid box are not fully independent because they share the same ACCO estimate derived from the selected cloud reference sector. Consequently, errors associated with the ACCO and the applied climatological correction are partly correlated among retrievals.

## **6. Validation & additional comparisons**

Clarify collocation windows (space/time) and whether validation uses daily or monthly aggregates (or both). Consider replacing crowded multi-panel plots with site-wise summary bars (bias, SD, r,slope) grouped by latitude/season/cloud regime, and add a map of sites colored by bias. Include layer-matched comparisons with TROPOMI O3\_TCL (tropics), OMI/MLS climatology, and a reanalysis (GEOS-CF/CAMS).

**Ans)** Monthly mean (July 2018–December 2022) ozone sondes are compared with monthly mean TROPOMI data within the same gridbox (0.5°x0.5°) containing the station.

We agree that spatial representations of station biases can provide additional information. However, the current multi-panel validation figures were designed to show the temporal evolution and station-to-station variability of the retrieval performance, which is important for assessing the algorithm behavior under different atmospheric conditions.

We have focused the validation on ozonesonde observations, which provide the most direct independent reference for evaluating the retrieved tropospheric ozone columns.

## 7. Bias analysis & future improvements

The manuscript explains biases largely on a case-by-case basis, which makes it difficult to identify clear priorities for improvement. Please outline a concrete plan for future algorithm development—specifying the main bias sources to be addressed, the diagnostics to be added, and the methodological changes you anticipate implementing.

**Ans)** Contribution to uncertainties identified in this study can be grouped into three main categories: (i) cloud-related errors, including the selection of cloud reference sectors ; (ii) climatological correction uncertainties, particularly in regions with strong regional deviations from the applied climatology; and (iii) dynamical atmospheric effects, such as stratospheric ozone variability and pollution events that are not fully captured by the current retrieval framework because of reduced UV sensitivity of the ozone retrieval near the surface.

A distance-weighted cloud sampling approach from the grid box for ACCO retrievals is planned in a future algorithm update.

We included this in the summary as “Contribution to uncertainties identified in this study can be grouped into three main categories: (i) cloud-related errors, including the selection of cloud reference sectors ; (ii) climatological correction uncertainties, particularly in regions with strong regional deviations from the applied climatology; and (iii) dynamical atmospheric effects, such as stratospheric ozone variability and pollution events that are not fully captured by the current retrieval framework because of reduced UV sensitivity of the ozone retrieval near the surface. A distance-weighted cloud sampling approach from the grid box for ACCO retrievals is planned in a future algorithm update.” **(Line number 488-493).**

### Specific comments

P.1 l-22: Please report relative as well as absolute TCO uncertainty (e.g., % of the column) and state recommended QC thresholds for “usable” data at low-TCO sites.

**Ans)** The absolute uncertainty of CLCD TCO450 was calculated as the monthly standard deviation of the retrieved columns, while the relative uncertainty was calculated as the ratio between the standard deviation and the mean TCO450 column. For low-TCO regions, where the ozone column is typically small (<25 DU), relative uncertainty becomes more important. Retrievals with relative uncertainty exceeding a defined threshold can be flagged for reduced reliability. For low-TCO conditions, the absolute uncertainty typically ranges between 2 and 10 DU, corresponding to relative uncertainties of approximately 15-45%. The larger relative uncertainties at midlatitude sites are associated with stronger ozone variability. Based on these results, a relative uncertainty threshold of 40% is recommended as a conservative criterion for identifying reliable low-TCO retrievals. Retrievals exceeding this threshold can be flagged as less reliable data.

| station | region | Mean<br>TCO | Absolute<br>uncertainty | Relative uncertainty<br>(%) | No. of months used<br>for calculations |
|---------|--------|-------------|-------------------------|-----------------------------|----------------------------------------|
|---------|--------|-------------|-------------------------|-----------------------------|----------------------------------------|

|                  |              |       | DU    |       | (2018-22) |
|------------------|--------------|-------|-------|-------|-----------|
| aquila           | Midlatitudes | 19.36 | 7.88  | 41.79 | 10        |
| ascension        | Tropics      | 15.09 | 3.14  | 24.25 | 10        |
| boulder          | Midlatitudes | 15.19 | 4.47  | 30.33 | 12        |
| broadmeadows     | Midlatitudes | 17.45 | 5.12  | 29.51 | 12        |
| churchill        | Midlatitudes | 23.69 | 10.7  | 45.57 | 12        |
| costarica        | Tropics      | 16.21 | 2.83  | 17.75 | 12        |
| debilt           | Midlatitudes | 21.93 | 9.44  | 43.87 | 9         |
| edmonton         | Midlatitudes | 20.97 | 9.57  | 46.54 | 12        |
| fiji             | Tropics      | 13.09 | 3.31  | 25.61 | 12        |
| goosebay         | Midlatitudes | 24.22 | 11.39 | 47.42 | 11        |
| hanoi            | Subtropics   | 17.96 | 3.22  | 18.31 | 9         |
| hauteprovence    | Midlatitudes | 21.79 | 8.57  | 39.81 | 11        |
| hilo             | Tropics      | 17.69 | 4.14  | 23.55 | 12        |
| hohenpeissenberg | Midlatitudes | 19.63 | 7.43  | 39.08 | 12        |
| irene            | Subtropics   | 16.11 | 3.29  | 21.06 | 12        |
| izana            | Midlatitudes | 19.04 | 5.36  | 28.88 | 9         |
| kingspark        | Subtropics   | 18.49 | 3.3   | 17.87 | 9         |
| kualalumpur      | Tropics      | 12.58 | 3     | 23.94 | 12        |
| lauder           | Midlatitudes | 14.81 | 5.21  | 35.68 | 12        |
| legionowo        | Midlatitudes | 21.96 | 9.35  | 43.13 | 10        |
| lindenberg       | Midlatitudes | 20.18 | 9.01  | 45.67 | 8         |
| macquarie_island | Midlatitudes | 18.04 | 8.55  | 47.62 | 12        |
| madrid           | Midlatitudes | 20.95 | 7.48  | 36.44 | 12        |
| nairobi          | Tropics      | 14.44 | 2.18  | 15.25 | 12        |
| natal            | Tropics      | 18.08 | 2.66  | 15.34 | 12        |
| paramaribo       | Tropics      | 15.82 | 3.05  | 19.36 | 12        |
| payerne          | Midlatitudes | 20.01 | 5.32  | 27.04 | 12        |
| pohang           | Midlatitudes | 22.79 | 9.77  | 42.75 | 5         |
| porthardy        | Midlatitudes | 22.72 | 7.93  | 34.84 | 11        |
| reunion          | Subtropics   | 17.93 | 3.5   | 20.2  | 12        |
| samoa            | Tropics      | 11.5  | 3.3   | 29.32 | 12        |
| trinidad         | Midlatitudes | 21.25 | 8.72  | 41.23 | 12        |
| tsukuba          | Midlatitudes | 21.59 | 6.8   | 31.6  | 7         |
| uccle            | Midlatitudes | 21.75 | 7.96  | 37.49 | 11        |
| valentia         | Midlatitudes | 24.44 | 10.28 | 42.19 | 11        |
| vignedivalle     | Midlatitudes | 20.59 | 7.6   | 38.52 | 10        |
| wallops          | Midlatitudes | 22.9  | 8.72  | 38.02 | 8         |
| yarmouth         | Midlatitudes | 25.25 | 11.38 | 44.87 | 11        |

**P4 I-92:** Specify the spatial/temporal resolution and version of the cloud parameters, and whether they are resampled to the ozone grid. Clarify consistency between cloud and total-ozone inputs.

**Ans)** The cloud parameters used in the CLCD retrieval are obtained from the TROPOMI cloud product (OCRA/ROCINN,), which provides cloud fraction, cloud-top height, and cloud-top pressure at the same spatial resolution as the TROPOMI total ozone product. The cloud and total ozone parameters are therefore directly spatially and temporally collocated in each TROPOMI pixel grid and no additional spatial resampling is applied.

**P4 I-100:** Provide monthly variance (and sample size) of ozonesonde TCO at each station. Clarify

whether sonde sampling variance is included in the retrieval uncertainty (the current Eq. (1) does not indicate this).

**Ans)** The ozonesonde measurements are used as an independent reference for validation and are not included in the CLCD retrieval uncertainty calculation. We added this to the manuscript for more clarity.

We added the following sentence: “The ozonesonde measurements are used as an independent reference for validation and are not included in the CLCD retrieval uncertainty calculation.” (**Line number 156-157**)

Equation (1) represents the uncertainty of the satellite derived daily TCO product and accounts for uncertainties in the daily TROPOMI total ozone column, ACCO, cloud fraction, cloud-top height, and the daily sampling of clear-sky pixels from the  $0.5^\circ \times 0.5^\circ$  grid box and cloudy pixels from the cloud reference sector.

The temporal variability and sampling uncertainty of the ozonesonde observations are instead reflected in the validation statistics. The standard deviations shown in Fig. 7 and Fig. 8 represent the standard deviation of taking the monthly mean of ozonesondes and TROPOMI.

**P5 I-131:** State the years used for climatology and discuss representativeness (e.g., trends/decadal changes). Include a sensitivity to the climatology epoch.

**Ans)** The climatological ozone profiles used in the CLCD-C approach are based on the TOMS V8 ozone climatology. The underlying climatology was constructed from SAGE II measurements from 1988-2001, MLS measurements from 1991-1999 where SAGE II data were unavailable, and balloon ozonesonde measurements from 1988-2002 (McPeters et al., 2007). The climatology provides monthly mean ozone profiles for 10-degree latitude bands. For the TOMS V8 retrieval, this climatology was further modified to include a dependence on total ozone, which is particularly important in the lower stratosphere.

Thus, the climatology represents atmospheric conditions from 1988 to 2002 and does not specifically represent the 2018-2022 period analyzed in this study. A sensitivity test using climatologies from different epochs was not performed in the present study.

The climatology provides the mean monthly and latitudinal distribution of ozone and is used only when the cloud-top-height variability is low and the CLCD-C approach is applied. In this case, only the ozone sub-column between the cloud-top height and the reference pressure level (450 hPa) is calculated, corresponding to an altitude region where long-term ozone trends are highly uncertain. Therefore, the representativeness of the ozone climatology does not significantly affect the retrieved TCO. The climatological correction is not applied when using the Theil–Sen regression approach (CLCD-T).

**P5 I-132:** Ten degrees is coarse for  $0.5^\circ$  boxes. Consider a finer-resolution or more recent climatology and quantify the impact on TCO.

**Ans)** The climatology is only used to estimate the vertical ozone amount between the observed

cloud-top altitude and the 450 hPa reference level, for which the resolution of the climatology is not relevant.

**P5 I-140:** Justify the cloud-fraction and cloud-top-height thresholds and provide a short sensitivity analysis.

**Ans)** The choice of  $CF \geq 0.8$  is a compromise between cloud coverage and retrieval quality. Higher cloud fractions are generally preferable because they reduce the contribution from the below-cloud “ghost column”, which is subtracted when deriving the above-cloud ozone column (ACCO). However, increasing the CF threshold progressively reduces the number of available observations. Previous studies have also shown that ACCO is relatively stable for  $CF \geq 0.8$  (Leventidou et al., 2016).

Regarding the choice of cloud top height, lack of high reflective clouds outside the tropics is a challenge to retrieve tropospheric ozone. Outside the Pacific sector, high reflective clouds are less frequent, and low-level clouds rarely reach the reference altitude of 270 hPa. Consequently, greater adjustments to the effective cloud top pressure may be required during the standardization of ACCO to the reference altitude, which increases uncertainty.

Figure.1 presents a global map of cloud top heights under cloudy conditions ( $CF \geq 0.8$ ) for 2022, highlighting that high clouds are predominantly observed in the tropics ( $20^\circ \text{ S} - 20^\circ \text{ N}$ ). Beyond  $20^\circ$ , the majority of clouds lie below approximately 3 km. The histogram of cloud top heights in non-tropical regions ( $20^\circ - 60^\circ$ ) shown in Figure 7.1b further supports this observation. It reveals that over 40% of clouds beyond  $20^\circ$  are below 1-2 km, with an average cloud top height close to 3 km. Setting the threshold below 2 km would include a larger number of low clouds, which provide limited sensitivity for ACCO retrievals, whereas a higher threshold would substantially reduce the number of available cloudy observations. We therefore selected 2 km as a compromise between maximizing data availability and ensuring sufficient cloud height for a meaningful above-cloud ozone retrieval.

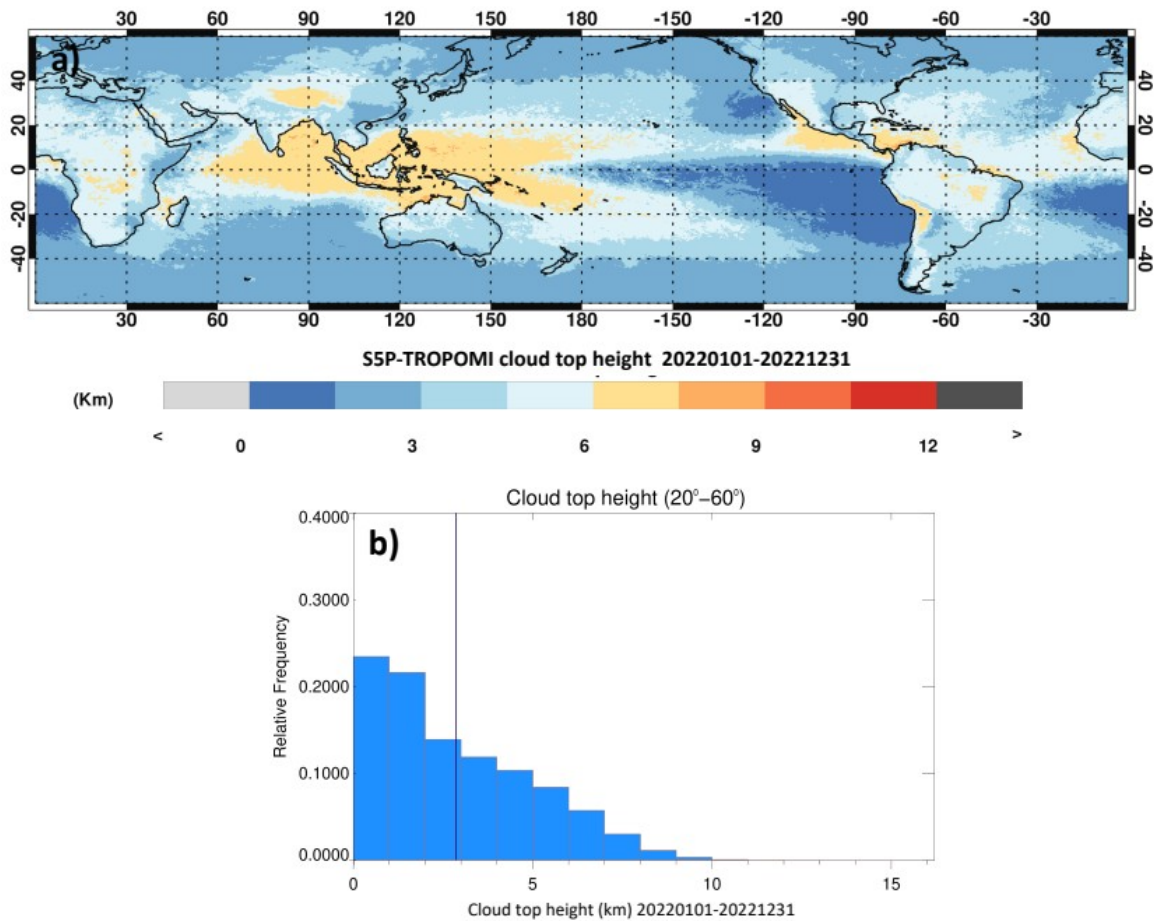


**FIGURE 1:** Global map of average cloud top height (km) under cloudy conditions ( $CF \geq 0.8$ ) based on 2022 data, and (b) corresponding histogram for cloud top heights outside the tropics (latitudes  $\geq 20^\circ$ ). The dark blue vertical line represents the average cloud top height.

**P6 I-150:** Clarify handling of cirrus, multi-layer, low clouds (e.g., low optical thickness, clouds below 2km). State any screening and its effect on coverage.

**Ans)** The CLCD retrieval does not explicitly classify or separately screen cirrus, multi-layer clouds, or low clouds based on cloud type or optical thickness. Instead, it uses the standard TROPOMI OCRA (Optical Cloud Recognition Algorithm) /ROCINN (Retrieval of Cloud Information using Neural Networks) cloud information provided for the total ozone retrieval. OCRA provides the cloud fraction, while ROCINN-CRB ("clouds-as-reflecting-boundaries") provides an effective cloud-top height, with clouds represented as Lambertian reflecting boundaries (ESA, 2021). For simplicity, we refer to this effective cloud-top height as the cloud top height.

Thus, the cloud representation is a simplified, effective representation of the scene rather than an specific treatment of individual cloud types or cloud layers. In particular, specific identification of cirrus, multi layer clouds, or optically thin or low clouds is not performed, as such a detailed cloud classification is computationally demanding and is not used in trace gas retrievals.

**P6 I-164:** Please clarify the data flow: Are retrievals performed daily per  $0.5^\circ$  box and then aggregated to monthly, or are any steps done on monthly composites?

**Ans)** The CLCD product is generated at daily resolution on a  $0.5^\circ \times 0.5^\circ$  grid and then monthly averaged. The reliability of individual daily retrievals depends on the availability of sufficient clear-sky and cloudy observations within each grid cell and the cloud reference sector. In regions with sparse sampling, random variability and sampling-related uncertainties can be significant on a daily scale. For this reason, the validation in this study is based on monthly mean data.

**P6 I-165:** Report how often and under what conditions negative ACCO/TCO occur.

**Ans)** We assign quality flag 5 when the retrieved TCO becomes negative. A negative TCO occurs when the retrieved ACCO is larger than the total ozone column (TOZ), since TCO is the difference between TOZ and ACCO. We analysed the occurrence of negative TCO cases caused by 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, compared with about 24% in both the subtropical and tropical regions.

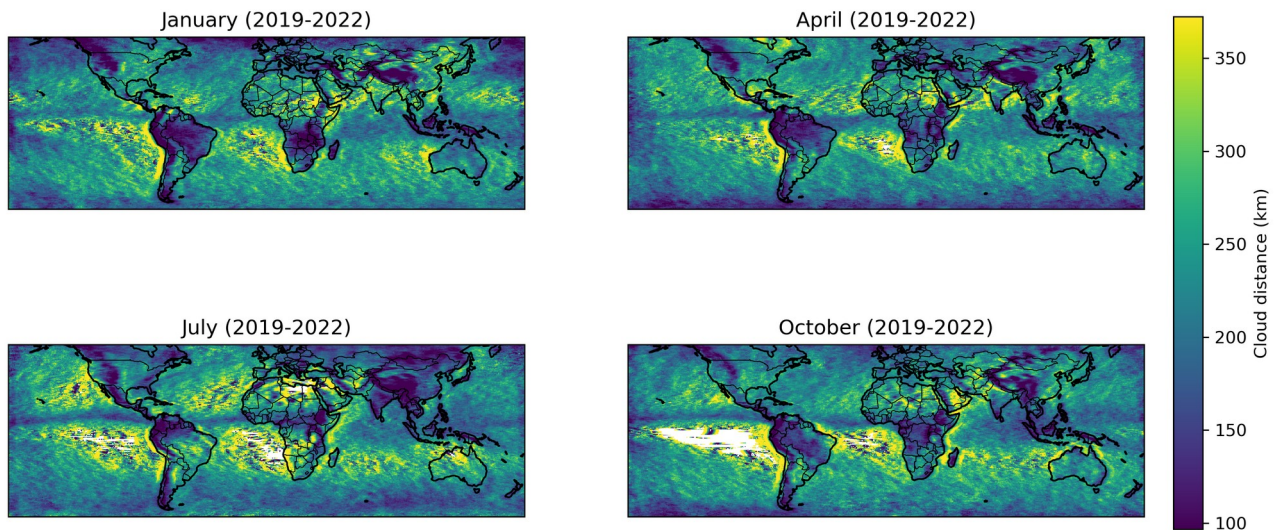
Overall, negative TCOs are more common at midlatitudes compared to tropical and subtropical regions. This might be related to the larger variability in stratospheric ozone (even though the homogeneity criteria were applied)

**P8 Figure 3:** Please clarify the total number of TROPOMI footprints contributing to each  $0.5^\circ \times 0.5^\circ$  grid box.

**Ans)** On average, each  $0.5^\circ \times 0.5^\circ$  grid box contains approximately 135 footprints in the midlatitudes, 133 footprints in the subtropics, and 143 footprints in the tropics, respectively. Of these, approximately 52, 47, and 48 footprints were cloudy, respectively, while approximately 83, 86, and 95 footprints were clear-sky observations. Thus, the cloudy footprints accounted for about 35–36% of the total observations, with the remainder being clear-sky observations.

**P11 Figure 6: (e)** Does the cloud reference sector change seasonally for a given box? If this is the case, please provide the distribution of selected radii by month and region.

**Ans)** Yes, the selected cloud reference sector can vary seasonally for a given grid box. The radius expands from the initial search distance 60 km until a sufficient number of cloud pixels (minimum 20 ACCO measurements) is obtained, with a maximum limit of 600 km. Therefore, regions and seasons with higher cloud availability generally require smaller reference sectors, whereas periods with fewer clouds result in larger selected radii. Please find the following figure of spatial cloud distance distribution with seasons for valid TCO retrievals.



**(f)** Define - distance-to-cloud edge precisely (units, edge detection). Explain the sharp transitions and how mean distances can vary from  $\sim 400$  km to  $\sim 50$  km. Quantify how often boxes have no clouds within  $\geq 4^\circ$  and how such scenes are handled.

**Ans)** We do not define or detect cloud edges in this paper. Instead the distance to the cloud is defined as the mean of distances (in km) between the center of the  $0.5^\circ \times 0.5^\circ$  retrieval grid box and all suitable cloudy pixels within the radius.

The observed sharp transitions in distance arise from the spatial distribution of clouds. In regions with extensive cloud cover, cloud pixels are typically located within or close to the grid box, resulting in small mean distances ( $\sim 60$  km). In contrast, in cloud sparse regions, the nearest cloud may be several grid cells away, leading to much larger mean distances (up to  $\sim 400$  km).

In angular terms, a  $4^\circ$  threshold corresponds to approximately 400–450 km, depending on latitude. In cases where no clouds are detected within this radius around a grid box, the search is extended up to a maximum distance of approximately 600 km. If the number of available cloud pixels still remains below the minimum requirement of 20, the TCO grid box is assigned a fill value and excluded from further analysis.

We agree that remote clouds might contribute to uncertainties in ACCO due to reduced representativeness of clouds which we mentioned in the manuscript. The distance to the nearest cloud pixel was analyzed for all stations, using a threshold of 400 km (approximately corresponding to  $4^\circ$  angular distance). The fraction of retrievals with cloud distances exceeding 400 km varies between stations, ranging from **1% (Costa Rica)** to **28% (Izana)**. Most stations show values below 20%.

**P12 I-212:** Provide monthly ozonesonde TCO variance and collocation counts used in each comparison.

**Ans)** Due to the limited availability of ozonesonde measurements (up to about 4 measurements per

month), we calculated monthly statistics by combining data from all available years (2018–2022). For example, all January measurements from 2018 to 2022 were combined to obtain the January mean and standard deviation. The ozonesonde and CLCD observations were considered monthly collocated when they occurred within the same month for all four years.

**P13 I-241:** Please standardize product naming (e.g., CLCD-TCO) across the text, tables, and figures. For example, Table 1 uses CLCD-TCO, whereas Figure 8 uses TROPOMI–sonde. Use consistent terminology and explicitly indicate the vertical layer (e.g., surface–450 hPa) in figure labels/captions so it's clear whether the comparison refers to total column ozone or the TCO up to 450 hPa.

**Ans)** We entirely agree. Thanks for pointing it out. We now use CLCD-TCO for consistency.

**P13 I-269:** Please specify the kind of possible issues.

**Ans)** Clouds over Goose Bay are generally low in altitude and often originate from relatively distant locations (Fig. 8c and d). During boreal spring, the presence of remote, low-level and homogeneous clouds (Fig. 11b and 12b) favors the use of the CLCD-C approach for ACCO retrieval. As a result, the retrieved cloud-top pressures differ substantially from the reference level of 450 hPa, which leads to relatively large climatological corrections (up to about –10 DU; Fig. 8f) to adjust ACCO to the reference level. This strong correction could negatively bias ACCO at the reference altitude (Fig. 8b) and, in turn, lead to higher tropospheric ozone columns (Fig. 9a)

**P15 Figure 7 and P21 Figure 9:** Increase symbol sizes and axis fonts; choose more distinct line colors/symbols.

**Ans)** Updated the figures (**Figure 7 line number 245, Figure 9 line number 351**)

**P16 Figure 8:** The small multiples are hard to parse.

**Ans)** Updated the figure 8. (**line number 251**)

**P17 I-281:** Where high positive TCO bias is linked to remote low-level clouds, test whether the source is (i) ACCO estimation mode (CLCD-C vs CLCD-T) or (ii) the ACCO to ACCO above 450 hPa conversion. Show targeted sensitivity tests.

**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.

We analyzed the Yarmouth retrievals during late boreal winter and early spring (February–March) using data from all four years. Among the 48 available retrievals, 41 were processed using the CLCD-C method, which applies climatological corrections to adjust ACCO to 450 hPa. These corrections were often large, leading to ACCO being too low and consequently results in higher TCO<sub>450</sub>.

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)**.

It’s important to note that this behavior is not representative of all stations, as the dominant sources of bias vary depending on local cloud characteristics and atmospheric conditions. The different causes contributing to biased CLCD-TCO retrievals are discussed in detail in Section 5.1.1, *Causes of bias and variability in CLCD-retrievals*.

**P18 I-315:** Describe the atmospheric profiles and weighting-function used to convert ACCO to ACCO above 450 hPa, and quantify this term’s contribution to the uncertainty budget beyond climatology.

**Ans)** The conversion of ACCO from the observed cloud-top level to the 450 hPa reference level depends on the selected CLCD approach. For CLCD-C, the correction is derived using ozone climatological profiles. The climatological ozone profile between the observed cloud-top pressure and 450 hPa is integrated to calculate the ozone amount that must be added or subtracted to adjust ACCO to the reference altitude. For CLCD-T, no climatological correction is applied and ACCO is obtained from clouds at different cloud-top heights within the local reference sector are extrapolated to 450 hPa using Theil–Sen regression. The uncertainty associated with the altitude correction is included in the ACCO uncertainty budget. The contribution from cloud-top-height uncertainty is represented by  $u_{\text{ACCO}_{\text{CTH}}}$ , which is estimated using a cloud-top-height uncertainty of approximately 500 m and contributes less than 0.5 DU to the total TCO uncertainty (Leventidou et al., 2016). For CLCD-C, the additional uncertainty associated with the climatological ozone correction is considered within the standard deviation of ACCO ( $u_{\text{ACCO}}$ ), as it depends on the variability of the climatological ozone profile and the difference between the cloud-top altitude and the 450 hPa reference level.

**P20 I-390:** State that whether ozonesonde profiles are convolved with the same weighting (or simple box integration, as appropriate) before comparing with the derived TCO.

**Ans)** In this study, ozonesonde profiles are directly integrated to obtain partial ozone columns from the surface to 450 hPa, consistent with the definition of CLCD-TCO.

**P 28 Figure 14:** Explain why the latitude range is 30° S–30° N here while other figures (figures 5 and 6) use 60° S–60° N, or harmonize the ranges.

**Ans)** The different latitude ranges reflect the different design of the two algorithms. CLCT is optimised for the tropical region (30° S–30° N) using a different cloud reference sector geometry (Maratt Satheesan et al, 2024), whereas CLCD is applied over a broader latitude range (60° S–60° N). Therefore, Figure 14 focuses on the tropical band to allow a consistent and direct comparison between CLCT and CLCD over their relevant region, using the same time period and vertical column (surface to 450 hPa), while Figures 5 and 6 show the wider spatial coverage of CLCD.

**P29 Figure 15 and P30 Figure 16, 17:** The maps show pronounced topographic signatures (e.g., Tibetan Plateau, Rocky Mountain) with TCO values apparently lower than those reported by Liu et al. (2022) and Xu et al. (2024). Some differences may stem from layer definitions (surface–450 hPa here vs surface–tropopause or other in those studies). Please consider: (i) provide layer-matched comparisons by converting your product to surface–tropopause and surface–270 hPa where feasible, or by integrating the reference products to surface–450 hPa; (ii) include cross-comparisons with reanalyses (e.g., GEOS-CF, CAMS) at the same layer/grid. These additions would better demonstrate the robustness of the retrieval over complex topography.

**Ans)** In these figures, we compare TCO with other tropospheric pollutants (NO<sub>2</sub>, CO, HCHO) to check possible correlations. The gases are operational products of TROPOMI and each has its own vertical resolution (NO<sub>2</sub> and HCHO: tropospheric column up to the tropopause, CO: total column, with major contribution from the troposphere). In this paper ozone sondes are best suited to match the same partial columns from TROPOMI and sondes given the very high resolution of the ozone sonde measurements. Different definitions of the vertical extent of the tropospheric column requires additional assumptions when converting the columns to a common altitude range that will lead to additional error sources. This is why we limit the validation to comparisons with sondes.

The differences observed over elevated regions, such as the Tibetan Plateau and Rocky Mountains, are expected to be partly related to the different vertical column definitions and vertical resolutions of the retrievals.

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