Answers to comments of anonymous referee #2

Thank you very much for your comments and suggestions. Our responses are written in blue in the text.

General Comments:

This study presents a valuable long-term dataset of total ozone and aerosol optical depth (AOD) derived from Brewer spectrophotometer observations. The extended temporal coverage makes the work particularly relevant. Its scientific impact would be significantly enhanced if the dataset were made publicly available through established repositories such as the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) and/or EUBREWNET, and ideally registered with a DOI to ensure long-term accessibility and citation.

Related to World Ozone and Ultraviolet Radiation Data Centre (WOUDC), total ozone data (since 1993) for the Poprad-Gánovce station are already part of this international database. Reports are sent on a monthly basis. The raw data from Brewer 097 are sent to the EUBREWNET network multiple times per day (near real time), available since 2014. EUBREWNET then processes and provides TCO data. However, data submission to the World Data Center PANGAEA is also being considered.

The AOD retrieval methodology, originally described by Hrabčák (2018), is extensively detailed in the manuscript. I recommend condensing this section and referring to the original publication, focusing instead on the specific updates or modifications introduced in the current study.

The revised version of the manuscript will contain a significantly reduced amount of this section. However, the goal is to move most of the text to the appendix.

In contrast, the description of the total ozone retrieval process is relatively brief. It would be beneficial to expand this section to include details on the o3brewer software setup, including the application of the Standard Lamp correction. Calibration procedures, and how major repairs or maintenance events were handled is also valuable. Clarifying how calibration changes were applied retrospectively and outlining the traceability of Brewer #97 to the reference triad would improve the technical transparency of the study. Additionally, how does the IOS traveling standard compare with the reference triad over the 30-year period? This comparison is essential for assessing long-term consistency.

In view of the aforementioned proposals, two subchapters to which the proposals relate have been revised and expanded. The edited version looks like this:

2.2 Brewer ozone spectrophotometer

The Brewer ozone spectrophotometer (a single monochromator, model MKIV, No. 97) has been performing measurements at the Poprad-Gánovce station since 18 August 1993. It is a scientific instrument that operates in the ultraviolet and visible regions of the solar spectrum. The device enables measurements of the total vertical column of O_3, SO_2, and NO_2, as well as global UV radiation (from 290 nm to 325 nm, with a step of 0.5 nm). Using its optical system, the instrument decomposes solar radiation reaching the Earth's surface and selects predetermined wavelengths from the ultraviolet and visible parts of the spectrum, with stronger and weaker absorption by O_3, SO_2, and NO_2. Based on the differing absorption of radiation at these selected wavelengths, it is possible to derive the total amount of these gases in the vertical column of the atmosphere. Additionally, measurements of direct solar radiation can be used to determine the AOD. The Brewer also enables the calculation of TCO using measurements of diffuse solar radiation. However, for the analysis of the TCO in this study, only direct solar radiation measurements were used, as they are more accurate.

Since the beginning of its operation, daily tests have been performed on the Brewer spectrophotometer using internal lamps, and it undergoes calibration every two years. The instrument is calibrated by International Ozone Services (IOS) Inc. against the global reference group (Brewer Triad). IOS is a long-established company that provides worldwide ozone and UV calibration services to customers operating Brewer Ozone Spectrophotometer instruments (https://www.io3.ca/; last access: September 2025). The calibration is carried out during a calibration campaign, usually on site or in a neighboring country, using a traveling reference instrument No. 17. The Brewer No. 17, used by IOS for calibrating Brewers belongs to Environment and Climate Change Canada. When not travelling, it is stationed next to the World Brewer Reference Triad in Toronto and is frequently compared with the triad instruments.

The calibration of Brewer No. 17 is usually updated annually, and more frequently if required, based on the data collected in Toronto. Over the years, IOS has also taken the instrument, together with the triad instruments, to the Mauna Loa Observatory (MLO) in Hawaii, USA, for independent calibrations. These trips to MLO and the regular comparisons with the triad have resulted in differences of no more than 0.5 % in TCO values between No. 17 and the triad. Further details on the calibration of Brewer #017 can be found in Savastiouk et al. (2004), and the Brewer reference triad is described in more detail in Fioletov et al. (2005).

The measurements can be regarded as homogeneous. Occasional short interruptions occurred for technical reasons, but no extended gaps such as entire months are present. Regarding major technical interventions or problems, these can be summarised as follows: a secondary power supply board had to be replaced in January 2005. In February 2007, a micrometer was replaced, and during the calibration in May 2007, optical filter No. 3 was replaced and a BM-E80 high-frequency source was also repaired.

2.3 TCO calculation

The TCO data set consists of daily averages collected by the Brewer ozone spectrophotometer. These data cover the period from 18 August 1993 to 31 May 2024. All data used were derived from direct sunlight measurements obtained through the DS (direct sun) measurement procedure. A DS measurement is accepted only for an air mass factor of the ozone layer of less than 4 (as recommended by IOS), and it takes approximately 2.5 minutes. During this time, the density of solar radiation flux is measured five times for each of the five wavelengths. Consequently, five values of TCO in Dobson units (DU) are obtained from a single DS measurement, which are then used to calculate an average and a standard deviation. Only the measurements that meet the criterion (standard deviation ≤ 2.5 DU) are selected for further data analysis. The TCO was calculated using the Brewer spectrophotometer B data files analysis program v. 7.4 (O3Brewer) by Martin Stanek (http://www.o3soft.eu/; last access: May 2025). Brewer spectrophotometer data file (B-file) contains the raw data collected by the Brewer spectrophotometer.

The O3Brewer software employs initialization files that are typically updated during calibration and contain all necessary instrumental constants and settings. The TCO data set was derived using as many as 57 such files in total. This number is considerably higher than both the number of performed calibrations and the years of operation. The reason is that, when required (mostly due to major instrumental changes), the nominal two-year intercalibration interval was subdivided into shorter segments. Such finer partitioning was usually carried out retrospectively after the subsequent calibration. The key constants required for the calculation of TCO from DS measurements are determined and verified during calibration.

Among the most important are the ETC values and the absorption coefficients for O_3. In connection with the standard lamp (SL) correction, the initialization file contains the so-called "values of SL R6 and R5 from the last intercomparison." The SL test O_3 correction is performed such that the O3Brewer software begins reading the B-files 10 days prior to the selected time period in order to process the SL test results first and generate the "SLsmooth.prn" file, and continues until 10 days after the selected period. It is customary to perform the SL test three times per day. In addition, frequent mercury lamp tests are routinely carried out, usually when the internal temperature changes by more than 2 °C. Further information on the O3Brewer software can be found in the publicly available online documentation (http://www.o3soft.eu/o3brewer.pdf; last access: May 2025).

References:

Savastiouk, V., C. T. McElroy, and Lamb, K.: Calibrating the Brewer spectrophotometers with the travelling standard Brewer #017, in: Zerefos, C. (Ed.), Proceedings of the Quadrennial Ozone Symposium, pp. 577–578, 2004.

Fioletov, V. E., Kerr, J. B., McElroy, C. T., Wardle, D. I., Savastiouk, V., and Grajnar, T. S.: The Brewer reference triad, Geophys. Res. Lett., 32, L20805, https://doi.org/10.1029/2005GL024244, 2005.

I suggest to include the comparison of the presented dataset with existing observations archived in WOUDC (Station 331, (https://woudc.org/data/stations/331) and EUBREWNET (https://eubrewnet.aemet.es/eubrewnet/station/view/33).

Indeed. The authors agree with the Referee on the importance of assessing the compatibility of the TCO datasets provided as a product of different networks, as well as evaluating their compatibility with the dataset exploited in this study. After all, consistency between datasets will be essential to ensure that data processing has been carried out successfully. Hence, two basic comparisons have been performed, both based on monthly means. The first is a naive approach based on plotting the temporal evolution of the monthly TCO means obtained for each dataset, so that they can be compared visually (Figure 1). It is important to note that the EUBREWNET Lv 1.5 dataset dates back to 2013, much later than those used in this study and those from WOUDC.

The TCO data for the Poprad-Gánovce station in WOUDC are produced using the mentioned O3Brewer software. This is the same software that was used to calculate the total ozone data for the article under review. In particular, older data in WOUDC were calculated using previous versions of the software, and this may lead to small discrepancies, as the software has been continuously developed over the years. Further, it is important to note that the data submitted to WOUDC once per month for the preceding month also include daily averages derived solely from the calculation of TCO using measurements of diffuse solar radiation (so-called ZS measurements). This applies to days when it was not possible to retrieve TCO from DS measurements. ZS measurements are subject to considerable uncertainty. In the article under review, the TCO dataset is derived exclusively from DS measurements. A comparison of these two different data sets may therefore lead to discrepancies, particularly during months with a higher proportion of ZS measurements (November–February).

At first glance, it can be said that there is a general agreement between the datasets. However, some discrepancies can be identified at the extremes (maxima and minima) between the calculated monthly averages and those from WOUDC. Something similar is found when comparing the EUBREWNET TCO means with those of the other two datasets, as EUBREWNET values tend to be higher at the maxima and lower in the minima.

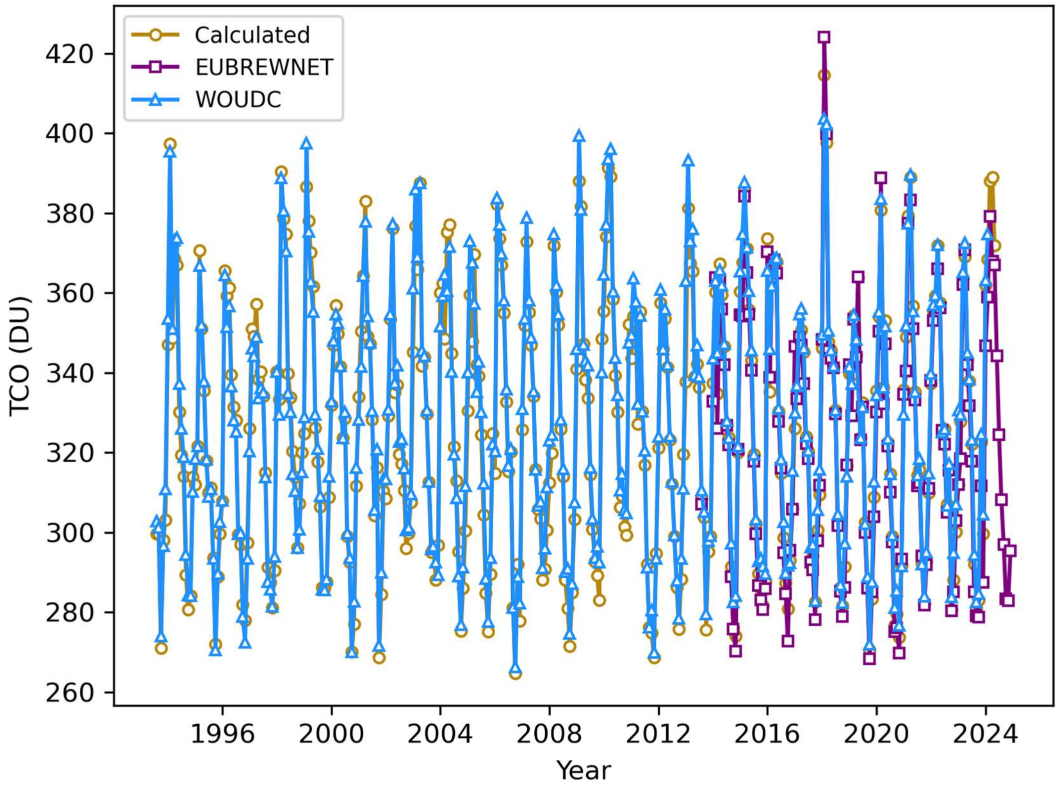

Figure 1 Evolution of TCO monthly means over time obtained from measurements by the Brewer ozone spectrophotometer in Poprad-Gánovce. Blue triangles correspond to values processed by the World Ozone and Ultraviolet Radiation Data Centre (WOUDC), purple squares are products of the European Brewer Network (EUBREWNET), and golden circles are the TCO values determined for this study. The WOUDC product (as well as the dataset used in this study) covers the period from August 1993 to May 2024, while EUBREWNET Lv 1.5 TCO values are available from August 2013.

The other analysis consists of evaluating the alignment of the data with respect to the line $y = x$ when plotting the TCO means corresponding to the same year and month (Figure 2). Furthermore, in order to quantitatively study the discrepancies, some statistical parameters have been computed: root mean square error (RMSE), std of the differences, mean bias deviation (MBD) and R^2. These are summarised in Table 1. In general, based on Figure 2, it can be stated that the three data sets are compatible, as the differences between them are relatively small.

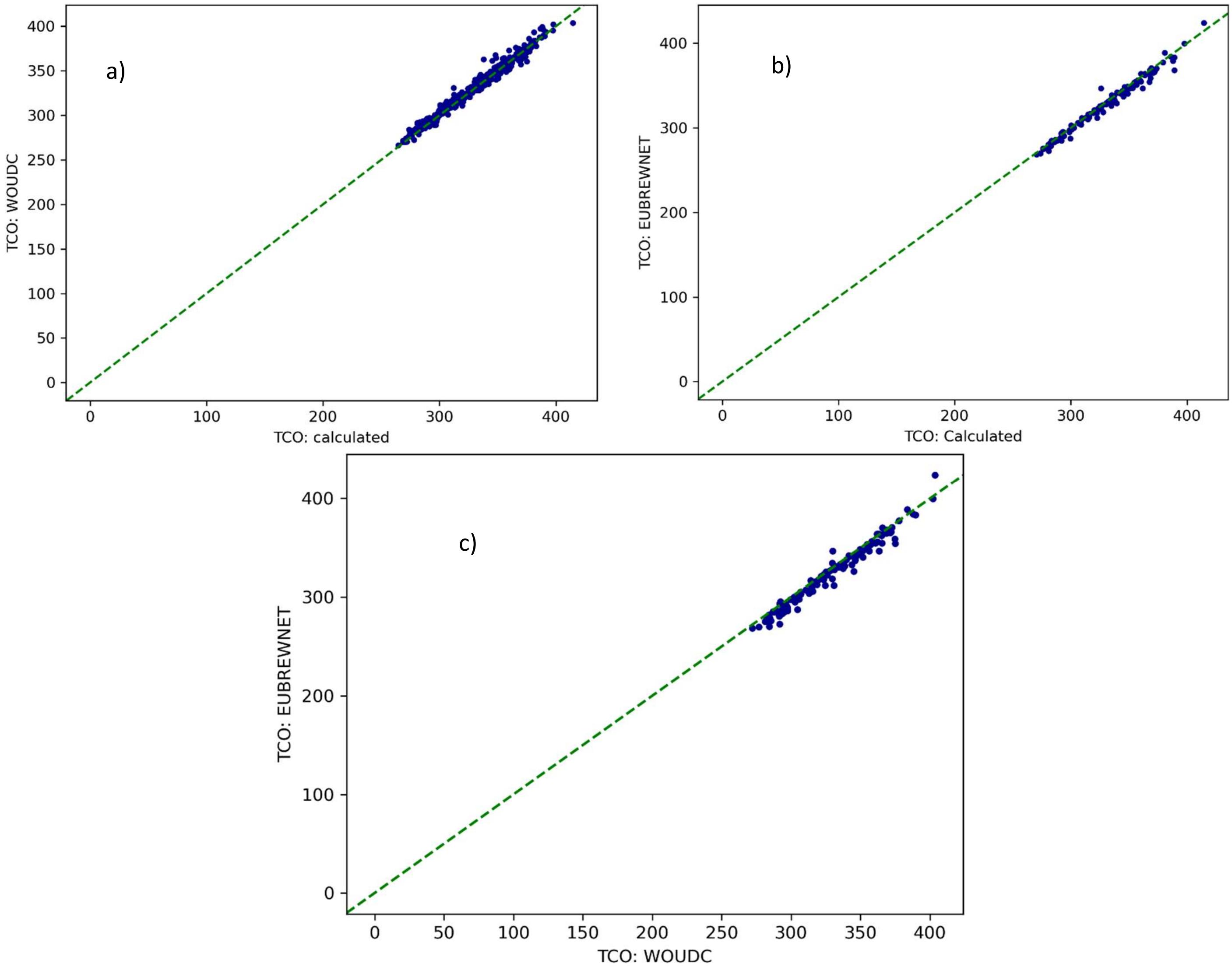

Figure 2 Scatter plots for the comparison between monthly TCO means provided by different datasets: (a) WOUDC and those determined for the analysis in the manuscript; (b) EUBREWNET and TCO for this study; and (c) EUBREWNET and WOUDC. The green dashed line indicates the plot $y = x$.

The discrepancies between WOUDC and the calculated TCO are the smallest, with an RMSE and standard deviation (STD) of the differences of 5.00 DU and 3.42 DU, respectively. In the comparison between EUBREWNET and the calculated TCO, these values are slightly higher (5.13 DU and 3.66 DU, respectively), but much lower than the values corresponding to EUBREWNET/WOUDC, 7.26 DU and 4.67 DU, respectively. However, it should be noted that, in the case of the latter two, the number of points compared is much smaller, as the EUBREWNET dataset begins in 2013. These statistical parameters measure the discrepancies between the compared values, showing less dispersion in the case of the comparisons involving the dataset used in this analysis. The same trend is observed with the MBD, which is -1.90 DU for WOUDC/Calc., 2.45 DU for EUBREWNET/Calc. and 4.48 DU for EUBREWNET/WOUDC. The negative sign for WOUDC/Calc. indicates that mean TCO for WOUDC are slightly higher than those calculated. Following the same reasoning, the calculated TCO are slightly higher than those of EUBREWNET, and the WOUDC values are consistently higher than those of EUBREWNET. All these parameters are much smaller than the measured TCO (~200-500) confirming the compatibility among the values of the different datasets. Finally, the $R^2 \approx 1$ values in each case indicate the goodness of the fits, supporting the claim regarding the agreement between datasets.

As mentioned above, the authors consider this comparison quite relevant to the study. Therefore, they consider that all or a part of this discussion can be added to the appendix of manuscript.

Table 1 Statistical parameters for the quantitative study comparing the TCO of the WOUDC and EUBREWNET networks, as well as the TCO values used in this study.

	RMSE (DU)	*STD* (DU)	MBD (DU)	R^2
WOUDC/Calc.	5.00	3.42	-1.90	0.98
EUBREWNET/Calc.	5.13	3.66	2.45	0.98
EUBREWNET/WOUDC	7.26	4.67	4.48	0.95

Note: We have not found any WOUDC or EUBREWNET AOD datasets to compare.

Single-monochromator Brewer spectrophotometers are subject to straylight interference, which introduces systematic biases in ozone and sulfur dioxide retrievals. This effect arises from the intrusion of longer-wavelength photons during short-wavelength measurements, leading to underestimation of trace gas concentrations (Savastiouk et al., 2023; Karppinen et al., 2014; Rimmer et al., 2018). To mitigate this, the dataset was filtered to include only observations with an airmass less than 4. However, as straylight effects scale with the ozone slant column (total column ozone × airmass), filtering based solely on airmass may be insufficient.

A double-monochromator Brewer spectrophotometer, which is not affected by straylight, has been operational at the station since 2015 (EUBREWNET Station 225). Comparative analysis between the single and double Brewer time series offers a means to validate the filtering approach. Moreover, straylight correction algorithms developed within EUBREWNET (Redondas et al., 2018) and by IOS (Savastiouk et al., 2023) can be use on the single brewer. Applying these corrections and assessing their impact on long-term ozone trends using the double Brewer as a reference could substantially improve the reliability of the dataset and enhance the interpretability of observed atmospheric changes.

We thank the Referee for drawing our attention to the issue of the stray-light effect in relation to the measurements of the Brewer spectrophotometer single monochromator, as well as for the recommended literature. At the outset, it is important to note that the correction for the stray-light effect has been determined during instrument calibrations only since 2023. This correction has also been taken into account in the calculation of TCO using the O3Brewer software, but only for data starting from 27 June 2023.

First, a comparison is presented between two Brewer spectrophotometers, the MKIV (single monochromator) and MKIII (double monochromator) models, which have been measuring TCO concurrently at the Poprad-Gánovce station since 2014. Pairs of DS measurements were compared, with a maximum time difference of 10 minutes between them. It was decided to perform the comparison starting from the first calibration of the MKIII model (No. 225) by IOS, which took place in 2015. Table 2 presents the results of individual statistical parameters, which are listed separately for each intercalibration period. We also note that the MKIII model experienced significant problems with the upper of its two micrometers during the first years of operation (until 2018), which may have caused certain deviations in the TCO measurements. This fact is likely reflected in the higher RMSE and standard deviation observed during the first two periods.

Because of the technical issue mentioned above, the comparison is of limited relevance (related to the investigation of the stray light effect) for the first two periods. Looking further at the MBD values for the last three periods, it can be seen that they range from -2 to 2 DU, which is essentially below 1 % relative to the typical TCO values. The Brewer MKIV Spectrophotometer Operator's Manual (SCI-TEC Instruments Inc., 1999) states that the TCO measurement accuracy is ±1 % for direct sun TCO. This indicates a quite good agreement between the two instruments. In any case, the negative MBD values in all periods except the last indicate some influence of the stray light effect. However, the magnitude of the positive MBD value in the last period, where TCO data are already corrected for the stray-light effect, suggests that this influence in the past was approximately within the range of typical instrumental error.

Table 2 Statistical parameters of the quantitative comparison of TCO between the Brewer MKIII and Brewer MKIV, both located at Poprad-Gánovce.

	RMSE (DU)	***STD* (DU)**	**MBD (DU)**	**R^2**
2015-06-01 – 2017-05-18	7.2	7.0	-1.9	0.967
2017-05-19 – 2019-05-15	5.0	3.7	-3.3	0.992
2019-05-16 – 2021-08-31	3.6	3.4	-0.9	0.993
2021-09-01 – 2023-06-26	3.9	3.3	-2.0	0.992
2023-06-27 – 2024-05-31	3.0	2.2	2.0	0.998

Given the very long measurement series, starting as early as 1993, it was decided to analyse the possible impact of the stray-light effect using a statistical analysis method described by Savastiouk et al. (2023). The method is based on plotting a large number of individual retrievals TCO as deviations from their respective daily medians. If little or no systematic daily variations in TCO are expected, then the differences from the daily medians should be almost randomly distributed around zero. Hence, any clear departure from zero increasing with ozone slant column density (SCD) could be a sign of the stray light effect (Savastiouk et al., 2023).

The analysis of Poprad-Gánovce data from Brewer No. 97 was carried out under the following conditions: all data were divided into 16 intercalibration periods; within each period the data were binned in intervals of 100 DU SCD; only days with a standard deviation of TCO < 3 DU were taken into account; and bins with a low number of points (< 50) were not plotted owing to insufficient statistics. Subsequently, for each intercalibration period, bins of SCD values and their corresponding relative deviations (averaged over the entire period) were linearly interpolated. The values in Table 3 were therefore obtained from the linear interpolation equation.

It is important to note that the values for 2024 already refer to the intercalibration period in which TCO data were obtained by applying a correction for the stray-light effect. TCO values for previous years could not be corrected for the stray-light effect. The deviation value for 2024 at SCD 1000 DU is -0.24 %, which is the same magnitude as the average over all 15 preceding periods. In the case of SCD 2000 DU, the mean value of -0.80 % is even lower than the 2024 value of -0.88 %. This indicates that the calibrations performed by IOS were generally able to reliably eliminate the influence of stray-light effect, with the degree of elimination reaching levels comparable to those obtained using the correction for the stray-light effect in the last period.

Savastiouk et al. (2023) report that, for a typical single monochromator Brewer, stray-light leads to an underestimation of ozone of approximately 1 % at 1000 DU ozone slant column density (SCD) and can exceed 5 % at 2000 DU. The average relative deviation for SCD 1000 DU (-0.24 %) over 15 intercalibration periods is approximately four times lower than the reported typical value. For SCD 2000 DU, the average relative deviation (-0.80 %) is even about six times lower. This comparison assures us that past values can also be used relatively reliably, as the effect of stray-light was largely eliminated.

Table 3 Time evolution of the percentage deviation of TCO from its respective daily median for SCD values of 1000 DU and 2000 DU over 16 intercalibration periods. The year indicates the midpoint of each two-year intercalibration period.

	1994	**1996**	**1998**	**2000**	**2002**	**2004**	**2006**	**2008**
1000 DU	-0.10	-0.20	-0.16	-0.27	-0.24	-0.15	-0.12	-0.19
2000 DU	-0.32	-0.56	-0.57	-0.75	-0.81	-0.54	-0.44	-0.58
	2010	**2012**	**2014**	**2016**	**2018**	**2020**	**2022**	**2024**
1000 DU	-0.28	-0.33	-0.32	-0.37	-0.18	-0.27	-0.37	-0.24
2000 DU	-1.05	-1.16	-1.10	-1.29	-0.70	-0.75	-1.30	-0.88

Initially, the goal was to correct TCO for the influence of the stray-light effect using the results of statistical analysis and the known stray-light constants from the 2023 calibration. However, in the end, after further consideration, it became clear that this approach was incorrect. In our case, it was decided not to apply a posteriori stray-light correction to the historical data (before calibration in 2023). The main reason is that, in earlier calibrations, the ozone absorption coefficient was often derived together with the extra-terrestrial constant (ETC) by regression against a reference instrument, in order to obtain agreement with the reference Brewer. As a consequence, the resulting absorption coefficient frequently deviated from the value determined from the dispersion test. This procedure effectively compensated, at least partly, for the stray-light effect of the calibrated instrument.

If one applies the recently determined stray-light constants to the historical datasets, it would also be necessary to adjust the corresponding ETC and absorption coefficient in a consistent way; otherwise, the recalculated TCO values would no longer match the original results. For this reason, applying only the new stray-light constants without simultaneously updating both ETC and the absorption coefficient would not yield reliable results. A potential re-evaluation of the historical Brewer No. 97 data series since 1993 would, in principle, be possible. However, this would require a complete recalculation of the calibration of the Brewer No. 97 at Poprad-Gánovce against the reference instrument No. 17. This is therefore beyond the scope of the currently achievable possibilities, but it represents a challenge for the future.

Finally, we note that we are considering including this analyses in our article, with the key points likely to appear in the main text and additional details provided in the appendix.

Concernign the analysis of the series, i reconnice the difficulty to deal with a no signifciant ozone trend, could be more appropiae to use the Multiple Linear Regresion Methods like developed in LOTUS project (GitHub - usask-arg/lotus-regression) to assest the the influence of the tropopause height.

The authors greatly appreciate the Reviewer's suggestion to approach this analysis using the LOTUS regression methodology. Given that the amount of TCO in the atmosphere depends on various complex factors, a methodology based on assessing the relative influence of each factor on the temporal evolution of TCO may be promising for addressing this problem. LOTUS regression is particularly well suited to this case, as is has been designed to study the temporal evolution of atmospheric parameters. Thus, the factors considered by the model, called "predictors", characterise the atmospheric components and processes that can trigger changes in the levels of the parameter under study. In this case, the authors have worked with the basic set of predictors from pred_baseline_pwlt.

These are ENSO (related to the "El Niño" and "La Niña" ocean oscillations), SOLAR (which characterise the solar cycle), QBOA and QBOB (representing orthogonal components of the Quasi Biennial Oscillation), AOD (a model of stratospheric AOD, which takes into account phenomena such as volcanic eruptions or massive fires), linear_pre and linear_post (parameters representing long-term linear evolutions before and after 1997, respectively. The reason for choosing 1997 is that this is when ODS levels in the atmosphere reached their maxima and began to decline as a result of policies derived from the Montreal Protocol. The establishment of this year as a turning point is arbitrary and can be changed as appropriate, although this is not the case in this study); and K (constant, a predictor with no physical meaning that is required by the model). However, another predictor, HEIGHT, has been added to take into account the influence of the height of the tropopause, given the relevance of this parameter for TCO levels.

However, before applying the model, we had to make some adjustments. Since the series characterising the predictors begins in January 1979 and runs until February 2024, while our dataset ranges from September 1993 to May 2024, we had to limit the working time interval from September 1993 to February 2024. This meant rescaling the predictors, as these are constructed so that the mean and standard deviation of the series are 0 and 1, respectively. Thus, we computed the mean $\bar{x}$ and the std $\sigma(x)$ of the predictor series in pred_baseline_pwlt, considering only the data from September 1997 to February 2024 and determined the rescaled values of the predictor for each month, x_i', as $x_i' = \frac{x_i - \bar{x}}{\sigma(x)}$, where x_i is the value associated with the predictor x in month i. In this way, the mean and std of the rescaled values are 0 and 1, respectively. In the case of the HEIGHT predictor, we started with a series of monthly means of tropopause height values between September 1997 and May 2024.

Hence, the corresponding mean and std did not verify the aforementioned condition, so the same relationship was applied as to the other predictors in order to rescale the values. The importance of rescaling parameters lies in comparing the strength of each parameter. In fact, by rescaling all these predictors, they can be compared directly, allowing us to draw conclusions about which of them has the greatest influence on the evolution of the parameter. As of the TCO, we decided to work with monthly means, but introducing a set of predictors that take seasonal components into account, based on Fourier series (see this example).

The results of the analysis are summarised in Table 4. Four predictors show a highly statistical significant trend: ENSO, QBOB, Linear_post and HEIGHT (we will not take K into account, given its non-physical meaning), the latter having the greatest influence on the TCO. In fact, the trend is negative, as expected: a decrease in TCO may be related to an increase in the height of the tropopause. The effect of the B component of the QBO, which according to Wang et al. 2022 is zonally asymmetric, also seems to translate into a decrease in TCO. Conversely, a smaller -in absolute value- but positive slope for Linear_post could be interpreted as the existence of an increasing trend in TCO since 1997, which would be consistent with the reduction in ODS emissions into the atmosphere. The effect of ENSO on TCO appears to be positive, i.e. contributing to an increase in TCO. This has also been confirmed by other studies (e.g. Zhang et al. 2015, Li et al. 2024). Therefore, the significant role of natural atmospheric cycles in assessing the temporal evolution of TCO has been demonstrated, as well as the notable influence of the tropopause height on this parameter.

The authors consider the conclusions drawn in this analysis to be quite interesting and relevant to the article. For this reason, they believe that they can be added to the manuscript. Moreover, these results can be supported by the analysis suggested by Reviewer 1, which consists of eliminating the contribution of tropopause height to changes in TCO when studying the temporal evolution and observing the TCO time series without this contribution, resulting in an increasing trend in TCO, in line with the positive slopes obtained here in relation to ENSO and Linear_post.

Table 4 Results of the LOTUS regression analysis applied to the set of monthly TCO means from measurements taken at the Poprad-Gánovce station covering from September 1993 to February 2024. The analysis yielded a $R^2 = 0.88$. The slope value is an indicator of the weight of each parameter in the model, while the sign determines its effect on the TCO (positive causes an increase and negative a decrease). CI represents the confidence interval with a confidence level of 95%. Finally, the p-values indicate the significance of the trend. Those with $p < 0.01$ (highlighted in orange in the table) show very significant trends.

Predictor	Slope ($unit^{-1}$)	CI	p-value
ENSO	**1.8 ± 0.7**	**[0.5, 3.2]**	**0.007**
SOLAR	0.7 ± 0.7	[-0.7, 2.0]	0.341
QBOA	-0.8 ± 0.7	[-2.1, 0.6]	0.264
QBOB	**-3.1 ± 0.7**	**[-4.4, -1.7]**	**$1.3 \cdot 10^{-5}$**
AOD	0.4 ± 1.4	[-2.2, 3.1]	0.758
Linear_pre	10 ± 20	[-30, 60]	0.515
Linear_post	**2.0 ± 1.2**	**[-0.4, 4.3]**	**0.099**
HEIGHT	**-13.5 ± 0.8**	**[-15.2, -11.9]**	**$3.5 \cdot 10^{-43}$**
K	**323.6 ± 1.9**	**[319.9, 327.4]**	**0**

References:

- Li, Y., Feng, W., Zhou, X., Li, Y., and Chipperfield, M. P.: The impact of El Niño–Southern Oscillation on the total column ozone over the Tibetan Plateau, Atmos. Chem. Phys., 24, 8277–8293, https://doi.org/10.5194/acp-24-8277-2024, 2024.
- LOTUS regression in GitHub, https://usask-arg.github.io/lotus-regression/index.html. Last visited: 16/09/2025
- Wang, W., Hong, J., Shangguan, M., Wang, H., Jiang, W., and Zhao, S.: Zonally asymmetric influences of the quasi-biennial oscillation on stratospheric ozone, Atmos. Chem. Phys., 22, 13695–13711, https://doi.org/10.5194/acp-22-13695-2022, 2022.
- Zhang, J., Tian, W., Xie, F., Li, Y., Wang, F., Huang, J., and Tian., H.: Influence of the El Niño southern oscillation on the total ozone column and clear-sky ultraviolet radiation over China, Atmos. Environment, 120, 206-216, https://doi.org/10.1016/j.atmosenv.2015.08.080, 2015

Specific comments:

I suggest to Include on Figure 1 and 2 also the series of tropopause heights

Thank you for this suggestion. Figure 3 depicts daily means of tropopause height along with daily means of TCO values. Due to the great amount of data points, the opposite behaviour that both parameters show cannot be properly distinguished. For this reason, the authors have decided to not modify Figure 1 and substitute Figure 2a by Figure 4 below. In this plot, the inter-annual variation of the tropopause height, computed based on monthly means, has been included next to the annual cycle of TCO. Left vertical axis represents Tropopause height in m, while right vertical axis depicts TCO in DU. It can be noticed that both magnitudes show an opposite behaviour: TCO values peak on March (due to Brewer-Dobson circulation, as suggested in the article), coinciding with the minimum in tropopause height. The lowest TCO concentrations are detected in October, but the maximum in tropopause height occurs in August. Despite the shift, the annual cycle of tropopause height is in remarkable anticorrelation with the annual cycle of TCO.

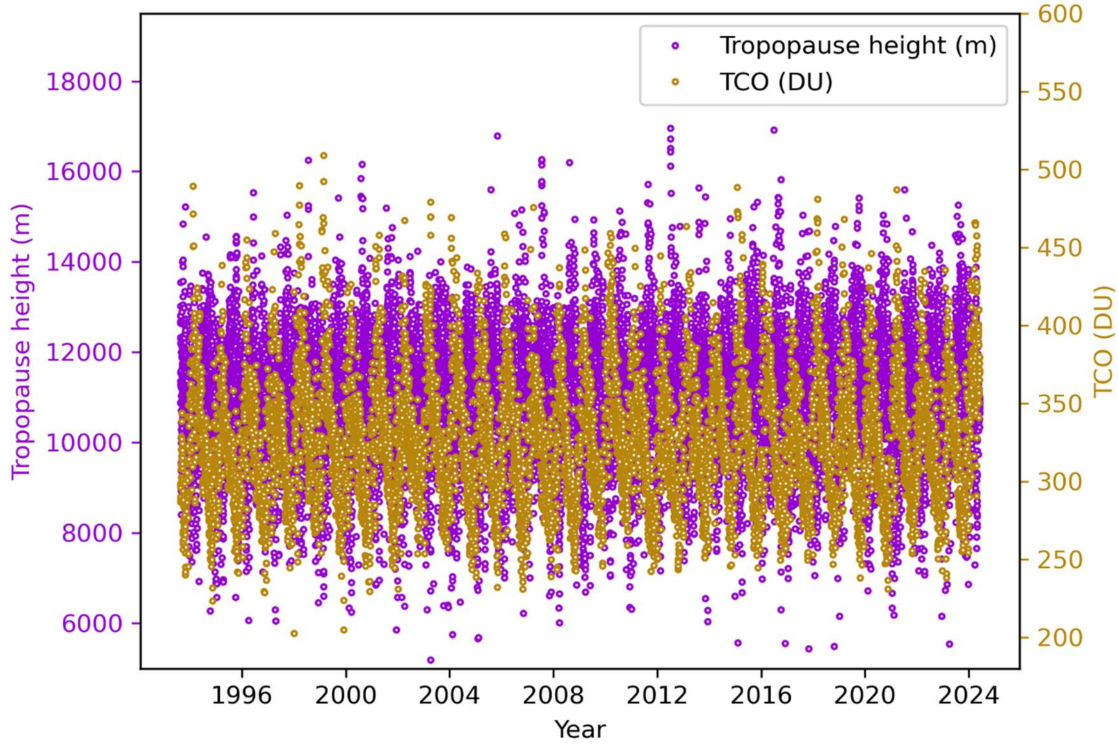

Figure 3 Daily mean values of tropopause height (left axis) and TCO (right axis) derived from measurements taken by the Brewer ozone spectrophotometer at Poprad-Gánovce from 18 August 1993 to 31 May 2024.

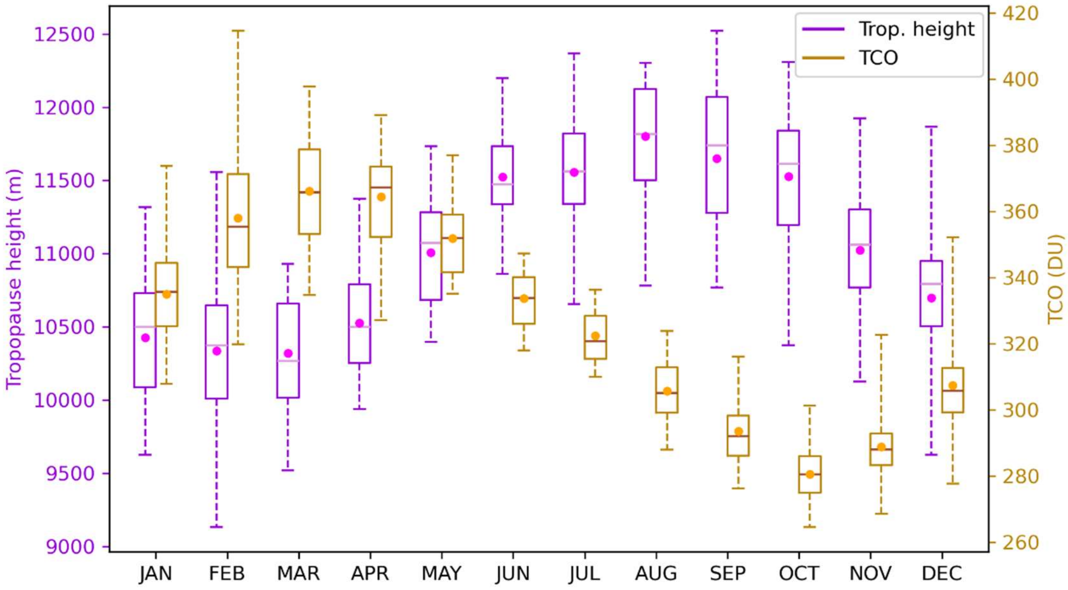

Figure 4 Boxplot showing the statistical distribution of the tropopause height (left vertical axis) and TCO (right vertical axis) for each month based on data from September 1993 to May 2024. The means are represented by solid points. The horizontal lines inside the boxes indicate the medians. The boxes extend from the 25th percentile ($\boldsymbol{U25}$) to the 75th percentile ($\boldsymbol{U75}$). Additionally, the lower and upper whiskers represent the corresponding minimum and maximum values, respectively.

L 97 -Homogeneus, please justify

The measurements can be regarded as homogeneous. Occasional short interruptions occurred for technical reasons, but no extended gaps such as entire months are present.

L135 Why the SO2 measurements are not reliable, please justify

The contribution of sulfur dioxide was neglected mainly due to its low impact (Arola and Koskela, 2004) and the inaccurate determination at the Poprad-Gánovce station. This site is generally considered rural with low anthropogenic influence, and SO_2 concentrations are therefore often close to the detection limit. In addition, the O3Brewer software settings for Poprad-Gánovce are not well optimised for the reliable retrieval of such low SO_2 values.

L190 how the filter attenuation are obtained

There are five ND filters and five wavelengths, resulting in a total of 25 required attenuation values. The attenuation values for the filters are determined during the instrument's calibration. The attenuation values are derived from the Filterwheel #2 Test and subsequently recorded in the FW2TEST file.

L 210 : which are the differences ?

Main differences compared to Hrabčák (2018):

1. Condition 2 (AOD limit at 320 nm):
   - Hrabčák (2018): AOD < 0.5
   - This study: AOD < 0.4
2. Condition 6 (standard deviation of TCO):
   - Hrabčák (2018): < 2.5 DU
   - This study: < 3 DU
3. Condition 7 (standard deviation of AOD):
   - Hrabčák (2018): < 0.07
   - This study: < 0.04
4. Condition 9 (determination coefficient of linear interpolation):
   - Hrabčák (2018): > 0.98
   - This study: > 0.99

In the manuscript, we plan to include the following explanation: Compared to the procedure described in Hrabčák (2018), several modifications were introduced: condition 2: the AOD threshold at 320 nm was reduced from 0.5 to 0.4, condition 6: the standard deviation of the daily TCO was relaxed from < 2.5 DU to < 3 DU, condition 7: the standard deviation of the daily AOD was tightened from < 0.07 to < 0.04, and condition 9: the required determination coefficient of the linear interpolation was increased from > 0.98 to > 0.99.

L230 : Not clear

In the end, the following criterion was applied to all determined ETCs within the given intercalibration period:

10. $$\frac{|ETC - AVERAGE(ETCs)|}{STDEV(ETCs)} < 1.5\ ,$$

where $AVERAGE(ETCs)$ is the average of the determined ETCs and $STDEV(ETCs)$ is the standard deviation. The threshold value of 1.5 in the 10th criterion was established in a manner analogous to that of the 8th criterion, i.e., it was selected based on the results of an optimization procedure. The objective was to exclude outlier values while ensuring a sufficient number of ETCs for the calculation of the final average.

L425: Table 5, include the errors

The authors greatly appreciate this suggestion and acknowledge the need to include this information when presenting slope values. For this reason, Tables 3 to 6 (corresponding to Tables 5 to 8 below) have been completed with the slope uncertainties.

Table 7 summarises the results from the linear regression analysis performed to quantify the seasonal dependence of TCO in tropopause height. Based on the R^2 and p-values (8.2×10^{-9} and 3.0×10^{-6}

for May/June/July and November/December/January, respectively), a statistically significant inverse relationship between TCO and tropopause height can be identified.

Table 5 Parameters obtained from the linear regression analysis of seasonal and annual TCO and AOD_{320}, based on weighted means from 1994 to 2023.

	TCO		**AOD_{320}**	
	Trend (DU/decade)	**R^2**	**Trend ($decade^{-1}$)**	**R^2**
Spring	0 ± 2	0.002	-0.074 ± 0.009	0.69
Summer	-1.6 ± 1.3	0.05	-0.068 ± 0.011	0.56
Autumn	-0.5 ± 1.7	0.003	-0.053 ± 0.009	0.58
Winter	1 ± 3	0.005	-0.032 ± 0.008	0.39
Annual	-0.2 ± 1.4	0.0005	-0.057 ± 0.005	0.82

Table 6 Parameters (trends and R^2) obtained from the linear regression analysis of AOD_{320} for each month of the year, based on data from September 1993 to May 2024. In addition, results from the Mann-Kendall test are also included. Specifically, $\boldsymbol{Z}$ represents the test statistic of the Mann-Kendall test, and $\boldsymbol{S}$ denotes Sen's slope. $\boldsymbol{Z}$ values indicating statistically significant trends at the 95 % confidence level ($|\boldsymbol{Z}| > 1.96$) have been highlighted in bold.

	Linear regression		**Mann-Kendall test**	
	Trend ($decade^{-1}$)	**R^2**	**Z**	**S ($decade^{-1}$)**
January	-0.021 ± 0.009	0.16	**-2.2**	-0.018 ± 0.012
February	-0.043 ± 0.012	0.30	**-2.8**	-0.044 ± 0.019
March	-0.069 ± 0.015	0.42	**-4.2**	-0.060 ± 0.019
April	-0.085 ± 0.016	0.49	**-3.8**	-0.09 ± 0.03
May	-0.067 ± 0.011	0.57	**-4.6**	-0.072 ± 0.013
June	-0.059 ± 0.013	0.42	**-3.2**	-0.05 ± 0.02
July	-0.062 ± 0.017	0.33	**-3.1**	-0.06 ± 0.02
August	-0.084 ± 0.019	0.42	**-3.4**	-0.08 ± 0.03
September	-0.070 ± 0.018	0.36	**-3.6**	-0.07 ± 0.02
October	-0.052 ± 0.010	0.50	**-4.2**	-0.049 ± 0.011
November	-0.039 ± 0.009	0.41	**-3.1**	-0.036 ± 0.014
December	-0.032 ± 0.013	0.19	**-2.1**	-0.023 ± 0.014

Table 7 Parameters resulting from the linear regression analysis of TCO means computed for different ranges of tropopause height, based on data from 18 August 1993 to 31 May 2024.

Months	**Slope (DU/km)**	**R^2**
May/June/July	-11.5 ± 0.6	0.98
Nov/Dec/Jan	-11.7 ± 1.0	0.94

Table 8 Parameters (trend and R^2) obtained from the linear regression analysis of tropopause height and TCO for each month of the year, based on data from January 1994 to December 2023. Additionally, results from the Mann-Kendall test are included. Specifically, $\boldsymbol{Z}$ represents the Mann-Kendall test statistic, and $\boldsymbol{S}$ denotes Sen's slope. $\boldsymbol{Z}$ values indicating statistically significant trends at a confidence level of at least 95 % ($|\boldsymbol{Z}| > 1.96$) are highlighted in bold.

	Tropopause height				**TCO**			
	Linear regression		**Mann-Kendall test**		**Linear regression**		**Mann-Kendall test**	
Month	**Trend (m/decade)**	**R^2**	**Z**	**S (m/decade)**	**Trend (DU/decade)**	**R^2**	**Z**	**S (DU/decade)**
January	-60 ± 90	0.016	-1.0	-110 ± 140	5 ± 3	0.06	1.2	4 ± 5
February	70 ± 120	0.011	0.8	100 ± 140	-2 ± 5	0.004	-0.5	-4 ± 7
March	90 ± 80	0.04	1.0	90 ± 130	2 ± 3	0.018	0.6	2 ± 5
April	80 ± 90	0.03	0.8	100 ± 120	-3 ± 3	0.02	-0.9	-3 ± 4
May	-30 ± 80	0.005	-0.4	-20 ± 100	1 ± 2	0.011	1.2	3 ± 3
June	130 ± 60	0.14	**2.2**	150 ± 80	-0.4 ± 1.7	0.002	-0.5	-1 ± 3
July	120 ± 80	0.08	1.6	200 ± 100	-0.7 ± 1.6	0.008	-0.5	-1 ± 2
August	200 ± 70	0.23	**2.9**	200 ± 100	-3.6 ± 1.8	0.12	-1.8	-4 ± 2
September	200 ± 100	0.14	**2.1**	250 ± 150	-3 ± 2	0.05	-1.4	-3 ± 3
October	100 ± 100	0.06	1.5	200 ± 130	-0.8 ± 1.9	0.006	0.1	0 ± 3
November	150 ± 90	0.09	1.9	200 ± 100	2 ± 2	0.03	1.0	2 ± 3
December	90 ± 100	0.02	0.7	70 ± 130	0 ± 3	$5 \cdot 10^{-6}$	-0.2	0 ± 4

L450: Include reference

This statement certainly requires a reference. The authors have also modified it, changing “contributes” to “may contribute”, as ozone depletion depends on several factors, not just on the increase in tropopause height.

With respect to the references, Meng et al. 2021 related the increase in the height of the tropopause to the troposphere warming due to climate change. Furthermore, Match et al. 2022 stated that global warming increases the height of the troposphere, which favours ozone depletion due to chemical processes and reduces its transport into the lower stratosphere.

The modified text will be:

The increase in tropopause height, primarily related to rising temperatures in the troposphere due to increased concentrations of greenhouse gases (Meng et al. 2021), may contribute to ozone depletion by shifting the ozone layer to higher altitudes (Match et al. 2022).

References:

- Match, A., & Gerber, E. P: Tropospheric expansion under global warming reduces tropical lower stratospheric ozone. *Geophysical Research Letters*, 49, e2022GL099463. https://doi.org/10.1029/2022GL099463, 2022.
- Meng, L., Liu, J., Tarasick, D. W., Randel, W. J., Steiner, A. K., Wilhelmsen, H., Wang, L., & Haimberger, L.: Continuous rise of the tropopause in the Northern Hemisphere over 1980-2020. Science advances, 7(45), eabi8065. https://doi.org/10.1126/sciadv.abi8065, 2021

References

- **Savastiouk, V., Diémoz, H., & McElroy, C. T. (2023)**. A physically based correction for stray light in Brewer spectrophotometer data analysis. Atmospheric Measurement Techniques, 16, 4785–4806. https://doi.org/10.5194/amt-16-4785-2023
- **Karppinen, T., Redondas, A., García, R. D., Lakkala, K., McElroy, C. T., & Kyrö, E. (2014)**. Compensating for the Effects of Stray Light in Single-Monochromator Brewer Spectrophotometer Ozone Retrieval. Atmosphere-Ocean, 53(1), 66–73. https://doi.org/10.1080/07055900.2013.871499
- **Rimmer, J. S., Redondas, A., & Karppinen, T. (2018)**. EuBrewNet – A European Brewer network (COST Action ES1207), an overview. Atmospheric Chemistry and Physics, 18, 10347–10353. https://amt.copernicus.org/preprints/amt-2018-157/amt-2018-157-RC1.pdf