Reply to Anonymous Referee #2 review of the manuscript acp-2025-3963

Evaluation of factors affecting TOC and its trend at three Antarctic stations in the years 2007–2023

David Tichopád on behalf of all co-authors

We sincerely thank Anonymous Referee #2 for the time dedicated to reviewing our work and for the constructive feedback. Your valuable comments have significantly contributed to the improvement of our manuscript.

Please find our answers below (in red)

General Comments:

This manuscript describes a long-term time series analysis of ground-based records from three stations in Antarctica. The authors use the multiple regression model developed by the LOTUS group, with additional parameters optimized for variability at polar latitudes. The authors additionally analyzed MERRA-2 reanalysis output to assess the spatial distribution of the various parameters. The study is very relevant and the manuscript clearly written and well-referenced. The figures, tables and supplemental material are clearly presented. I recommend publication after the following issues are addressed.

We thank the reviewer for their careful reading of our manuscript and for the constructive comments. We appreciate the positive assessment of the study and have addressed all points raised in the revised manuscript.

Specific Comments:

L68: The sentence starting “While the B199 instrument offers very high accuracy…” is somewhat confusing. I believe the 0.15% from Scarnato et al. refers to the precision rather than the accuracy and is for the double Brewer instrument in general. Also, the wording should clarify that the direct sun measurements are the most precise. Something like: “To assure the highest precision, only direct sun measurements were utilized.”

Corrected

L99: Including a different data set, particularly at the endpoints, can have a notable impact on the trend even if the offsets are small. It will be difficult to compare with other studies because of the specific period of the fit, starting later in the recovery time period, in 2007. To address this, I think it would be instructive, either in the paper or in the supplemental material, to show a figure similar to Figure 5 but use the OMI overpass and MERRA-2 overpass data at each station (time series shown in Figure 2) to get an idea of the possible range of values from different data sources. There are notable differences in the time series as shown in Figure 2, including a small drift at Troll and Concordia.

Thank you for highlighting the sensitivity of the trend estimates to the choice of dataset and to the length of the fitting period. We agree that differences at the endpoints, even if small, may influence the derived trends and complicate comparisons with other studies. In response to this comment, we have added supplementary figures analogous to Figure 5 (Fig. R1 and R2), in which the trends are calculated using OMI overpass data and MERRA-2 overpass data at each station (based on the time series shown in Figure 2).

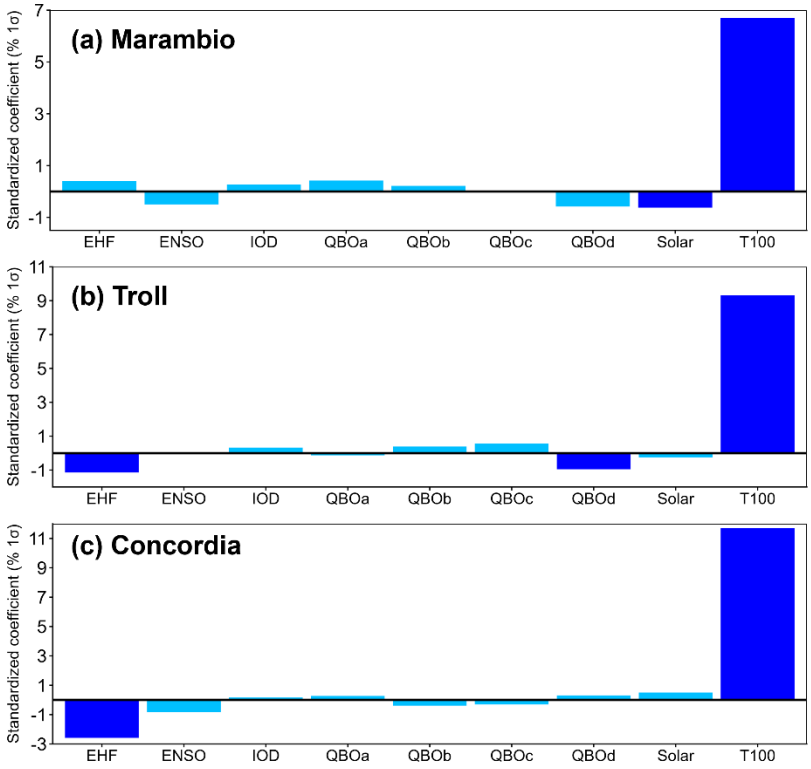

Fig. R1 Predictor contributions to the annual regression fit at Marambio (a), Troll (b) and Concordia (c) for OMI overpass data. Standardised coefficients indicate the percentage change in TOC associated with a one standard deviation change in the predictor. Light blue bars denote predictors whose effect on ozone is not statistically significant (p-value of the coefficient <0.05).

When comparing all three figures (the compiled time series, the OMI overpass data, and the MERRA-2 data), small differences are apparent. At Marambio, the influence of T100 remains statistically significant, but QBOd becomes statistically insignificant in both the OMI and MERRA-2 datasets, while the solar factor becomes statistically significant. At Troll, the results are similar, except that the QBOc predictor is no longer statistically significant when using OMI and MERRA-2 data. At Concordia, the solar factor is not statistically significant when using either the OMI or MERRA-2 datasets.

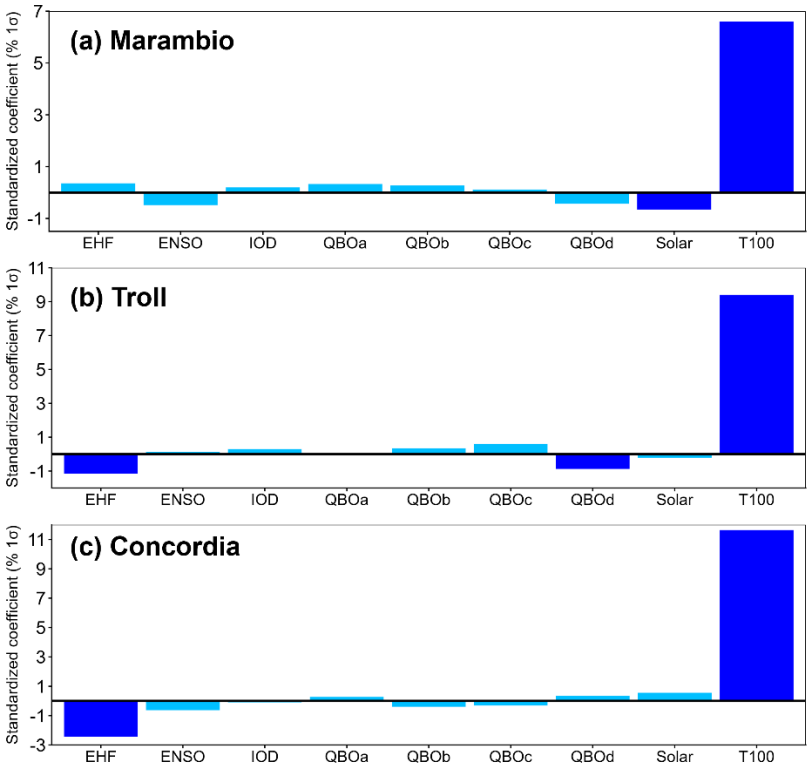

Fig. R2 Predictor contributions to the annual regression fit at Marambio (a), Troll (b) and Concordia (c) for MERRA-2 data. Standardised coefficients indicate the percentage change in TOC associated with a one standard deviation change in the predictor. Light blue bars denote predictors whose effect on ozone is not statistically significant (p-value of the coefficient <0.05).

L235: Here and throughout the manuscript when discussing the QBO fits, can the authors explain the relevance of the individual QBO terms. I understand why multiple EOF principal component time series are used, but I do not believe these terms can be physically interpreted individually. For example in Figure 4, rather than show the individual terms, I believe this result is more easily understood if the terms are re-added to represent the net QBO variability. I would also be interested to know if the net QBO fit was statistically significant at each station. I believe the authors can apply a joint F-test to determine this. Also in Figure 10, a panel can be added that shows the reconstruction of the net QBO for the two years. I realize the figures and discussion are set up to address the individual terms, I would just like to see the examples of the full QBO signal expressed in DU in Figures 4 and 10, and if possible an estimate of the significance of the full QBO signal.

Thank you for this very valuable comment. In response, we have added a curve representing the sum of the four QBO components in Figure 4, as well as in Figures S4 and S5. We have also assessed the statistical significance of the net QBO fit using a joint F-test. The results show that the combined QBO signal is statistically significant only at Troll ($F = 4.51$, $p = 0.002$), while for the other stations it is not statistically significant. These results have been included in the revised manuscript.

We have also added the net QBO signal to Figure 10 and performed a joint F-test for each grid point (Fig. R3), which will be included in the supplementary material and referenced in the manuscript.

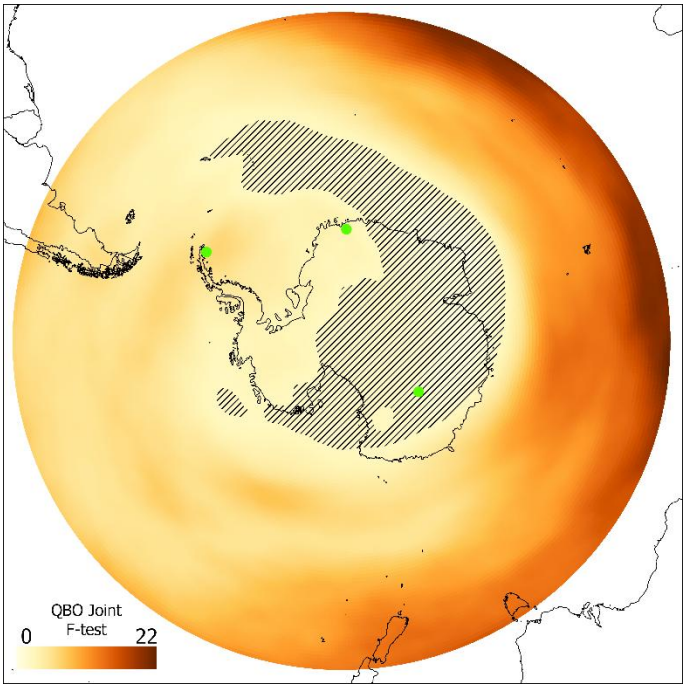

Figure R3 Joint F-test for the net QBO signal for each grid point. Colours indicate the F-statistic values. The unshaded area is statistically significant ($p<0.05$).

Line 245: This is a nice figure, can the trend term be added as well? It is a little out of place because it covers all three stations, it might fit better after the regression fits for each station are presented, but this change is not mandatory. The same results using the OMI and MERRA-2 overpass time series would be very interesting as mentioned before, this plot could be part of the supplemental information but referred to in the text. Such a plot would also make it easier for the reader to compare the results in Figure 9 to the station results.

We thank the reviewer for this helpful suggestion. As noted in our response to the L99, the comment corresponding plots based on the OMI and MERRA-2 overpass datasets have been added to the supplemental material. We have also calculated the individual trends using the LOTUS regression and present these results in a supplementary table (Tab. R1). In addition, we have reorganized the section containing this figure to improve clarity and readability.

Table R1 Linear trends of TOC at the three Antarctic stations (Marambio, Troll, and Concordia) in 2007–2023 compiled time series, OMI and MERRA-2 data. The table presents the estimated trend (DU/decade), the associated uncertainty, the p-value, and the adjusted R^2 for each station. A statistically significant trend is marked in bold ($p < 0.05$).

Station	Fit results	Trend [DU/decade]	Uncertainty [DU/decade]	p-value	Adjusted R^2
Marambio	Compiled	**3.43**	±3.22	0.04	0.94
	OMI	**4.58**	±2.97	0.00	0.95
	MERRA-2	**4.20**	±3.00	0.01	0.95
Troll	Compiled	-1.09	±3.91	0.58	0.97
	OMI	2.42	±3.30	0.15	0.98
	MERRA-2	1.59	±3.31	0.34	0.98
Concordia	Compiled	1.15	±4.25	0.59	0.95
	OMI	1.47	±4.61	0.53	0.95
	MERRA-2	0.47	±4.40	0.83	0.95

Line 392: I would caution the authors not to assign too much causality to some of the fits. For example, when comparing 2019 and 2020, the QBOa and QBOd terms switch signs, as do the ENSO and IOD terms, but this is due to the proxy signals changing sign over this period, not due to the conditions of a warmer or colder polar stratosphere (see Figure S1). The temperature and EHF are related to the polar dynamics, but the QBO/ENSO/IOD terms vary according to the time scale of those forcings and just happen to change sign from 2019 to 2020. It is possible that the QBO phase impacts the wave activity and thus the vortex, but to show this the authors would need to assess the QBO phase over a series of cold and warm polar conditions. The text reads as though a warm vortex produces a QBO signal that is one sign, and a cold vortex a QBO signal of the other sign. This may not be the intention, but it should be carefully worded to avoid inaccurate (or at least unproved) associations.

We agree that the sign changes in the QBO, ENSO, and IOD terms between 2019 and 2020 are driven by the behaviour of the proxy time series themselves, and should not be interpreted as a direct causal response to warmer or colder polar vortex conditions. Our intention was not to imply such a causal relationship, and we have revised the text accordingly to avoid any unintended interpretation.

Conclusions: It would be interesting to see comparisons of the derived trends with trends from other studies. This might be difficult because of the variable time periods between studies. But again, a comparison with the satellite and reanalysis overpass time series would be useful in place of outside comparisons.

We thank the reviewer for this suggestion. The derived trends are compared with OMI overpass data and MERRA-2 reanalysis in Table X (see comment at L245). This comparison provides context and allows assessment of the consistency of our results with these datasets.

Technical Corrections:

Title: suggest spelling out TOC in the title

Corrected

L19: any time the trend is given, the uncertainty estimate should be included.

Corrected

L43: suggest wording change: “a strong wave-1 disturbance developed”

Corrected

L50 Jonson -> Johnson

Corrected

L116: SBUV can be removed here, it is not included in the description and SBUV is not relevant to MERRA-2 after October 2004.

Corrected

L156: please clarify in the text, the equatorial zonal mean wind at seven pressure levels between 70-10 hPa were used

Corrected

L189: the lowest mean deviation

Corrected

L212: suggest removing “and the lowest in September-October and January -April” I think it is sufficient to say the largest variability is in November-December.

Corrected

L230: Can the authors say more here about whether the ENSO results agree with the study by Lin and Qian (2019).

Corrected

We have decided to remove this sentence, as a direct comparison with Lin and Qian (2019) is difficult because their study focuses on the spatial distribution of ozone.

L235: suggest adding tick marks for each year to make the plot easier to read.

Tick marks for each year are already included in the plot, which should facilitate reading the time series.

L263: Is this because Marambio is sometimes in the collar region?

It is indeed possible that the observed behaviour at Marambio is influenced by its occasional location within the collar region.

L284: The last sentence in this paragraph is largely repetitive. I suggest removing it or revising the last sentence of the previous paragraph to include this information.

Corrected

L311-312: The Marambio trend in November is positive, and the trend for September is increasing but also not statistically significant. Suggest: “Interestingly, the trends for October and November and decreasing but not statistically significant at all stations except Marambio in November, while the trends for September at all stations are increasing, but also not statistically significant.”

Corrected

L320: suggest adding tick marks for each year to make the plot easier to read. Also in Figures S1 and S4.

Tick marks for each year are already included in the plots, including Figures S1 and S4, to facilitate reading the time series.

L328-329: suggest simplifying the text here, possibly “Time series analysis at each grid point shows the spatial distribution of the fits to each parameter, which are expressed using standardized coefficients of determination.”

Corrected

L338: suggest Lin and Qian (2019) shows that …

Corrected

L346: the equatorial zonal wind at seven pressure levels between 10 and 70 hPa.

Corrected

Line 359: Jonson -> Johnson

Corrected

Line 359 and 361: can remove “Studies by” and “A study of” to simplify the text.

Corrected

L376: suggest wording clarification: “slowdown the heterogenous reactions that activate Cl on the surface of PSCs, thus slowing ozone depletion and suppressing the formation… “

Corrected

Line 380: Was the further decomposition of the EHF done in the Shen et al., 2020 study or in this study? If in the Sten et al study I suggest “Based on further decomposition of the EHF, Shen et al. (2020) found… “ to make it clear this was not part of the current work.

Corrected

L413: include trend uncertainty value in text

Corrected