Response to the Referee #2's comments on "The impact of El Niño–Southern Oscillation on the total column ozone over the Tibetan Plateau" (egusphere-2023-1452)

We thank the referee for the helpful comments. His/her insights have improved the quality of our paper. The manuscript has been revised and improved in response to the referee's comments and suggestions. Below is a point-by-point response (in black) to the referee's comments (in blue) followed by any modifications to the manuscript (*in italics*). We have updated explanation for clarification and included a caveat in discussion on the uncertainties of the results.

The line numbers for the changes correspond to the clean/revised manuscript version.

Response to ***Anonymous Referee #2***

General comments

The article "The impact of El Niño–Southern Oscillation on the total column ozone over the Tibetan Plateau" submitted by Yang Li et al. studies the connection of the ENSO to the total column ozone (TCO) above the Tibetan Plateau (TP). By investigating long-term satellite data from the C3S, the chemical transport model TOMCAT, and the water vapor and ozone data set SWOOSH, the authors connect the positive (negative) anomalies in the Niño 3.4 index to anomalies in the TCO and ozone profiles. The study of this topic is very interesting and the article would be well suited for ACP and an important contribution to the community. In addition, the article is well-written and mostly understandable.

We thank the referee for these positive comments.

There are, however, some aspects to the scientific presentation and content that need major revision before recommendation for publishing. First of all, the analysis restricts to the assessment of anomalies averaged over multiple Niño events, there is no mention of the spread between events. A comprehensive study would benefit greatly from assessing, or even briefly showing, the variability between different events and the dependence of the anomalies on the Niño 3.4 Index.

Thank you. We agree that there would be some spread between events. However, as we have stated in [Lines 355-356] and Figure 9, the relationship is significant with limited spread ($p < 0.01$), meaning the changes of ozone during the majority of ENSO events are in coherent with the composited anomalies.

Furthermore, the analysis of this article is restricted to correlations between different anomalies. Drawing conclusions on the causation of the TCO stays, therefore, difficult. Especially, since, as the authors mention, the TCO is influenced by multiple effects. There is, however, no apparent attempt to decouple the considered effect of the Niño from the other processes.

Good point. The QBO is another potential important source of interannual variability, which we have now analyzed by adding a plot comparing our results with and without QBO. By doing this, we show that our results are not sensitive to the QBO, and make sure the impact of ENSO on the TP TCO is robust during December–May with or without the QBO signal. Please see [Lines 186–205] and Figure 2.
Yes, we need to be cautious when making conclusions by the statistical methods. We have now added a caveat in the discussion to show the uncertainties and limitation of this study.
[Lines 406–410]: "*Our study focuses on the diagnosed ozone changes over the TP during ENSO episodes using both observations and a chemistry transport model TOMCAT as well as several statistical methods, which will have some uncertainties due to large internal variability of ozone and limited ENSO events. Future work is needed for a better understanding of tangible ENSO impacts with more observed ENSO events and a full-chemistry climate model*".

Lastly, the explanation of the positive TCO anomaly by a downward shift of the ozone profile is lacking. How would a mere downward shift alter the total ozone in a column? Or is partial column ozone considered? The authors should explain the mechanism behind profile shifting leading to increased ozone in a clearer way in order to make it comprehensible.

The shift of ozone profile represents the partial column ozone anomalies associated with TH change. We have updated explanation for clarification.
[Abstract, Lines 28-30]: "*This reduced temperature associated with El Niño events causes a decrease of the tropopause height, which tends to replace ozone–poor tropospheric air by ozone–rich stratospheric air in the UTLS and hence leads to the increase in TCO*".
[Results, Lines 272-276]: "*Approximately 90% of ozone in the atmospheric column resides in stratosphere; the ozone concentration is much lower in the troposphere with a gradual transition at the tropopause. Therefore, a decrease of tropopause height (TH) will tend to replace ozone–poor tropospheric air by ozone–rich stratospheric air in the UTLS region, and thus increase the partial column ozone, which in turn contributes to the TCO increase, and vice versa for an increase of TH (e.g. Schubert and Munteanu, 1988; Salby and Callaghan, 1993; Steinbrecht et al., 1998; Chipperfield et al., 2003; Varotsos et al., 2004; Tian et al., 2007)*".

Specific comments

1. Line 47: "high atmospheric transparency" This region is below the Asian Tropopause Aerosol Layer, which should affect the atmospheric transparency as well. Consider adding a comment on its effect.

We have added the associated citation into the revised manuscript [Line 41].

2. Lines 54–58: Please expand a bit on these processes: Brief description of the mechanism (at least for the dominant effects). Is there seasonal varying importance of the different processes?

Yes, the brief description of the mechanism and seasonal change has been revised as noted [Lines 48-57]: "*These studies have argued that the summertime TCO low is caused by changes in mass exchange between troposphere and stratosphere due to the stratospheric variability, for example the synchronisation of the quasi–biennial oscillation (QBO) and seasonal cycle (Chang et al., 2022), and tropospheric changes, for example the high topography and thermal forcing of the TP (Ye and Xu, 2003; Kiss et al., 2007; Tian et al., 2008; Guo et al., 2012) and enhanced convective activity in summer (Liu et al., 2003; Bian et al., 2011). In comparison to the summertime TCO change, less attention has been paid to the TP TCO variability during other seasons. It is worth highlighting that the interannual variability of TP TCO is strongest from wintertime to springtime (Figure S1 of the Supplement). The QBO, a significant natural mode of interannual variability (e.g. Fusco and Salby, 1999; Kiss et al., 2007), could not only contribute to the summertime TP TCO change via modifying the SAH (Chang et al., 2022), but also correlate with wintertime TCO variation (Zhang et al., 2014; Li et al., 2020)*".

3. Lines 62–64: You explain the EN part of ENSO here. Please add a sentence on the Southern Oscillation, i.e., the atmospheric anomalies of the ENSO.

Thanks, done as
[Line 59-61]: "*ENSO represents a periodic fluctuation of the tropical Pacific sea surface temperature (SST) and sea level pressure during warmer phase (El Niño) and colder phase (La Niña)*".

4. Lines 64–69: Why are these regions "showing the significant interannual variability"? Please rephrase or expand.

Rephrased in [Lines 63-66].

5. Lines 72–73: Expand on what limits the satellite measurements. Probably, there is only a limited number of ENSO events in this time period. The sentence could also be understood that there are deficiencies in the measurements themselves. Please clarify.

Clarified.
[Lines 68-69]: "……*their results are based on very limited ENSO events since the satellite era……*".

6. Lines 95–96: ”The long-term stability of the TCO product is within the 1% per decade level” It’s not clear to me what this means, please expand.

Expanded.
[Line 87-88]: “*The long-term stability of the TCO product with reference to the ground–based monitoring networks is within the 1% per decade level*”.

7. Line 103: ”and has 12 levels per decade in pressure ranging from 316 to 1 hPa (31 pressure levels)” Do you mean 12 time steps per decade, i.e., 10-monthly data? Please clarify what the ”12 levels per decade” refer to.

Sorry for the confusion. Corrected.
[Line 98]: “……*has 31 pressure levels from 316 to 1 hPa*”.

8. Lines 109–111: Why not use the SST from ERA5? Please briefly comment.

The ERA5 data is reanalysis data product, which assimilates the observations in the ECMWF model. The HadISST1 only contains observations and has been widely used by groups worldwide.

9. Lines 111–113: Why use the Niño 3.4 index instead of other indices? Please briefly comment.

The Niño 3.4 index has an advantage over other indices for the beginning, end, duration, and magnitude of ENSO events (Trenberth, 1997).

10. Line 158: This is a running 3-month mean, right? Consider stating this in the text.

Yes, we have revised it in [Lines 155-156] and caption of Figure 1 [Line 166].

11. Lines 179–181: Please state that this refers to the bars in Fig. 2.

Done.
[Line 176]: “……*is greater pre–May than post–May (bars in Figure 2a)* ……”.

12. Line 185: ”as one could be expected from”, remove either ”one” or change ”be expected” to ”expect”.

Corrected. We have changed “be expected” to “expect” as noted [Line 203].

13. Lines 181–186: The variance is much higher in TOMCAT than in the observations (50–100%). Is this accounted for in the following considerations? I would not call this ”reasonable magnitude” but still the variability is well-matched. Maybe you could use the systematic difference found here to put the later results into perspective.

Good point. We have used the systematic difference to explain the possible reason for the differences in later composited results.
[Lines 177-184]: “*Although the TOMCAT overestimates the SD (**Figure 2a**) because of its biases (Li et al., 2022), it can be seen from **Figure 2a** that TOMCAT matches well the SD variability and correlation coefficients with ENSO in the C3S dataset. These biases of TOMCAT simulation are likely due to (1) the incomplete presentation of complex atmospheric process in the TOMCAT, or (2) the uncertainties in the TOMCAT’s meteorology (ERA5) reanalysis scheme (Mitchell et al., 2020; Dhomse et al., 2021). Nevertheless, the high correlation (above 0.95, **Figure 1**) of TP TCO between C3S dataset and TOMCAT simulation from December to May give us confidence that the TOMCAT is able to capture the observed variability in TP TCO during these seasons and that we can thus use it to investigate the impact of ENSO on the TP TCO change*”.

14. Lines 212–221: Here, all Niño events have been composited. It is unclear how the composition was performed: e.g. average or weighted average according to the Niño 3.4 index? Please specify. In addition, it is unclear what the behavior for individual Niño events is. Please give at least a comment about the variability throughout the different events.

Sorry for this. The composition is calculated by the average of the variable during ENSO events. This has been specified now in Method [Lines 134-135]: “*It is calculated by the average of the variable during ENSO events and its statistical significance is tested by the two–tailed Student’s t–test*”.
For the second part of the comment, the behavior for individual El Niño event has been shown in the scatter plot with each dot representing a single ENSO event (Figure 9), which has confirmed the significance of the composited results and the relationship between ENSO and ozone-related changes.

15. Figure 4: Plotting the (standard) deviation of the profiles, i.e., the profile ± variability, would be an easy way to show the variability between different events. Consider adding these intervals (e.g. as shading) to the figure.

Thanks for the suggestion. We have revised Figure 4 to show the standard deviation of the profiles.

16. Lines 253–254: It is unclear to me how a downward shift of a profile could singularly alter the total content of ozone in the respective column. Either the partial column ozone is changed, e.g., ozone up to 50hPa, or there has to be an increase in production/mixing from adjacent regions. A stretching (or compression) of the profile, for example, would change the TCO. Please clarify the mechanism that, in the end, leads to increased TCO.

The shift of ozone profile represents the partial column ozone anomalies associated with TH change. We have expanded the explanation to clarify the mechanism. Details, please refer to our response to the **General comment 3**.

17. Line 262: Are the latitude-height sections averaged in longitude or taken as a cross-section at a fixed longitude? Either way, please specify.

Specified by adding "*averaged in longitude (from 75.5°E to 105.5°E)*" in [Line 284].

18. Figure 6: The change in TH alone (located mostly between 30°N –35°N) does not explain the widespread change in ozone stretching to at least 42°N. Locally, I agree that the TH might contribute but do you have hypotheses on the cause of the northern part of the anomalies?

The changes in the northern part of the anomalies are very likely due to the horizontal mixing by advection, in line with previous studies (Neu and Plumb, 1999; Plumb, 2002).

19. Lines 299–304: Could there be a surface temperature anomaly above the TP due to Niño events? If not or of the opposite sign to the Indian Basin SSTA, it could strengthen the argument of the land-sea contrast.

Yes, the 2-m surface air temperature anomaly above the TP is negative during El Niño events, which is of opposite sign to the SSTA in the Indian Ocean. We have added a sentence in our revised manuscript to strength the argument of the land-sea contrast [Lines 327-328].

20. Line 338 & Fig. 9: Specify what "temperature associated with air thickness" refers to more clearly. I suppose this is the temperature as calculated from Eq. 3?

Yes, it is from Eq.3, which has been added it into caption of Figure 9 and [Lines 331-333].

21. Lines 344–346: There are some severe outliers in Fig. 9, e.g., La Nina with -2T thickness. Are the outliers generally corresponding to a weaker Niño index? Consider coloring the scatter plot with the Niño 3.4 index instead of blue/orange. But, of course, there could be various other processes involved in singular events.

Fair point. We have revised Figure 9b using different colours according to the Niño 3.4 index.

Technical comments

1. Line 119: ”to the 1984–2021.” There seems to be a word missing here: average, period?

Thanks. Added.

2. e.g. line 219: ”from the December of the ENSO’s mature phase to the May of” the use of ”the” in front of a month is usually incorrect and reads cumbersomely. Consider removing ”the”. The same is true for time periods throughout the text, e.g., ”the YEAR–YEAR” →”YEAR–YEAR” (unless using a trailing noun such as ”the YEAR–YEAR period”).

Removed.

3. Line 266: ”further results” → ”further contribute”

Done.

4. Line 288: Consider dropping ”as” in ”is considered as an important”.

Done.

5. Line 295: ”is a response of SSTA” → ”is a response to SSTA”

Done.

6. Figure 7: Consider enlarging the text on the color bars.

Done.

References

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