Response to the Referee #1's comments on "The impact of El Niño–Southern Oscillation on the total column ozone over the Tibetan Plateau" (egusphere-2023-1452)

We again thank Referee #1 for making detailed comments and very useful suggestions to improve the paper. The manuscript has been revised and further improved in response to the referee's comments and suggestions. Below is a point-by-point response (in black) to the comments (in blue) followed by the corresponding changes in the manuscript with track changes (*in italics*). Some key general points relevant to the comments are:

- In the first revised version, we used correlation coefficient, composite method, hypsometric equation, and TOMCAT results to study our topic, and we had a caveat of correlation analysis in summary and discussion.
- In the first revised version, the high correlation between C3S data and TOMCAT (from DJF to MAM) gives us confidence that the TOMCAT is able to capture the observed variability in the total column ozone (TCO) over Tibetan Plateau (TP), and we also discussed the reasons of TOMCAT biases.
- In the new revision, we have now also compared the TP TCO with and without considering the ENSO signal to highlight the influence of ENSO on TP TCO.
- In the new revision, we have now added more details on Student's *t*-test and its statistical significance, and we also have revised the statistical significance of spread.
- In the new revision, we have further improved the abstract and conclusion.
- In the new revision, we have modified a caveat in the discussion to show the limitation and indication of Figure 9.
- In the new revision, the Tables 1-2 have been moved to method section and the download links of datasets have been moved to data availability.

The line numbers for the changes correspond to the marked-up manuscript version.

Response to ***Anonymous Referee #1***

General comments

With respect to the original version of the manuscript, I believe that this revised version has addressed some of the main concerns raised by both reviewers during the first revision. However, many doubts remain and are not totally solved with the author's responses and changes. In particular, doubts remain about the almost exclusive use of the correlation coefficients, and the use of the Student's t-test to infer about its statistical significance (which is not clear) and also on the use of the statistical significance to infer about the spread. Indeed, both reviewers previously raised comments against the use of only anomalies averaged over multiple Niño events, without an analysis of the spread of the events. Similarly, both reviewers raised comments about the use of only correlation coefficients to draw conclusions on the TCO causal mechanisms. In this respect, I consider the responses and the changes applied not satisfactory enough. I urge the authors to carefully reconsider those comments and to greatly improve the analysis in this regard. Indeed, I believe that, those being the major comments raised by both reviewers during the first revision phase, they deserve better attention by the authors. The rest of more specific comments is provided below.

We thank the reviewer for suggesting that we reconsider the statistical method used in the analysis. In the first revised version, we used correlation coefficient, composite method, hypsometric equation, and TOMCAT results, and we had a caveat of correlation analysis. Now we have added new information included in the revision:

1) composite of TP TCO with and without the ENSO signal
2) more details on Student's *t*-test
3) correction of spread's statistical significance

Many studies have used correlation coefficients to investigate the linkage between two factors (e.g. Thompson and Wallace, 1998; Woolnough et al., 2000; Trenberth et al., 2015). Based on this point, we use correlation coefficient to find the relationship between ENSO and TP TCO. Our results show that there is a robust linkage between ENSO and TP TCO from DJF to MAM (Figure 2). To further make sure that our conclusion is convincing and the result is robust, in addition to the correlation coefficient, we reiterate that we also used the composite method, hypsometric equation, and TOMCAT results to study the linkage between ENSO and TP TCO. Our results show that the El Niño (La Niña) events correspond to the significantly positive (negative) TCO anomalies over the whole TP (Figure 3). To further clarify the influence of ENSO on TP TCO, we have added new information on composite analyses of TP TCO with and without ENSO signal (Figure 3 and Figure A1). Through comparing their difference, we find there is no significant TCO anomalies over the whole TP during El Niño and La Niña years when the ENSO signal is removed (Figure A1). This supports that ENSO has an influence on TP TCO. As correlation follows Student's *t* distribution with effective number, we use Student's *t*-test to infer about its statistical significance (please also see responses to *Specific comments 8 and 10*). However, the Student's *t*-test cannot infer the statistical significance of spread and we have revised the associated sentence (please see more responses to *Specific comment 15*). It is also noted that the correlation analysis has its limitation, which was the reason that we had added a caveat in summary and discussion in the first revised version.

Our detailed explanations and discussion of this point are as follows:

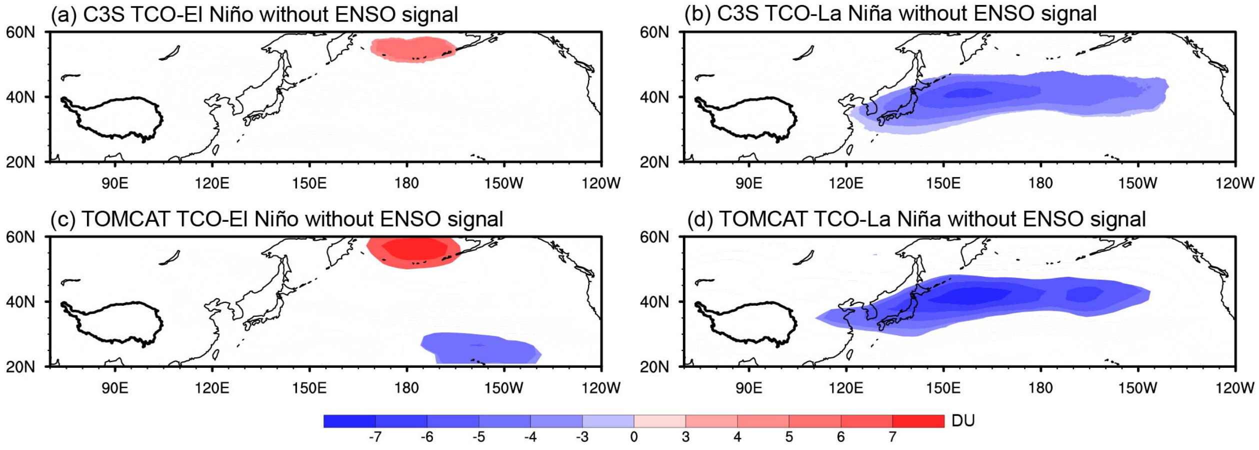
(1) The purpose of using correlation coefficient and the reason of using Student's *t*-test. In our study, we aim to find the linkage between ENSO and TP TCO variability by using observations and TOMCAT. For this purpose, we should first evaluate the performance of TOMCAT on TP TCO variability. Considering that correlation coefficient can evaluate whether model reproduces the observed variability (e.g. Wang et al., 2008), we use the correlation coefficient to evaluate the performance of TOMCAT on TP TCO variability. The high correlation coefficients (above 0.95

from DJF to MAM) give us confidence that TOMCAT is able to capture the observed variability in TP TCO. We can thus use it to investigate the impact of ENSO on the TP TCO variability (please also see response to *Specific comment 11*). In addition, many studies have used the correlation coefficient to investigate the linkage between two variables (e.g. Thompson and Wallace, 1998; Woolnough et al., 2000; Trenberth et al., 2015). Based on this point, we use the correlation coefficient to find the linkage between ENSO and TP TCO variability. Since the correlation follows Student's *t* distribution with effective number, the two-tailed *t*-test can provide some indication about the significance of the correlation. Please see more responses of Student's *t*-test and statistical significance to *Specific comments 8 and 10*. The Student's *t*-test cannot be used to evaluate the statistical significance of spread. We have revised the associated sentence, please see more responses to *Specific comment 15.*

(2) In addition to the correlation coefficient, composite, hypsometric equation, and TOMCAT results are also used in our study. In view of the fact that the relation between the positive and negative ENSO phases may not be linear, we further consider the two phases separately. For this purpose, we perform composite analyses for both phases to further investigate the linkage between ENSO and TP TCO. The composite method has been used by many previous studies (e.g. Thompson and Wallace, 2001). Figure 3 shows the El Niño events correspond to positive TCO anomalies over the TP, and vice versa for the La Niña events. We also use the hypsometric equation (equations 2-3) to investigate the influence of air thickness on tropospheric temperature. In addition, many studies show that TOMCAT performs well in reproducing the observed ozone variability (e.g. Feng et al., 2005; Singleton et al., 2005; Rösevall et al., 2008; Kuttippurath et al., 2010; Chipperfield et al., 2017, 2018; Griffin et al., 2019; Bognar et al., 2021; Feng et al., 2021; Li et al., 2022), due to information from field campaigns/lab measurements/reanalysis dataset and improved tracer transport and chemistry etc. In our study, we find that ENSO has an influence on TP TCO variability from DJF to MAM. During this period, the correlation coefficients between TOMCAT and C3S are above 0.95, suggesting that TOMCAT reproduces well the observed TCO variability.

(3) Comparing the composite analyses of TP TCO with and without ENSO signal, it is further suggested that ENSO has an influence on TP TCO. We use a regression method to remove the ENSO signal from TP TCO and then perform composite TCO during El Niño and La Niña years. This method of removal is similar to previous studies (e.g. Thompson et al., 2008; Li et al., 2017). After removing the ENSO signal, Figure A1 shows that there is no significant TCO anomaly over the whole TP during El Niño and La Niña years for C3S dataset and TOMCAT simulation. Comparing this result (Figure A1) to the composite with ENSO signal (Figure 3), it is suggested that ENSO has an influence on TP TCO. These discussions have been added into the revised manuscript [Lines 250–254]: "*To further clarify the influence of ENSO on TP TCO, we use a regression method to remove the ENSO signal from TP TCO and then perform composite TCO during El Niño and La Niña years. Without considering the ENSO signal on the TP TCO, both C3S data and TOMCAT simulation show that there is no significant TCO anomalies over the whole TP during El Niño and La Niña years (not shown). Comparing the TP TCO with and without the ENSO signal supports that ENSO has an influence on TP TCO*".

(4) We added a caveat of correlation analysis in summary and discussion of first revision. [Lines 440–443]: “*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 ENSO impacts with more observed ENSO events and a full-chemistry climate model*”.


(a) C3S TCO-El Niño without ENSO signal

(b) C3S TCO-La Niña without ENSO signal

(c) TOMCAT TCO-El Niño without ENSO signal

(d) TOMCAT TCO-La Niña without ENSO signal

Figure A1: Same as Figure 3, but without considering the ENSO signal on the TP TCO.

Specific comments

1. Lines 35-40: The explanation of the mechanism is not that clear. I would suggest trying to improve it.

OK. We have improved it. [Lines 28–34]: “*Our results suggest that the El Niño events impact the TP TCO via the following processes: (1) negative upper–level geopotential height anomaly associated with El Niño is responsible for a decrease in air column thickness; (2) the thickness decrease modulates reduced tropospheric temperature and thus favours a decrease in the tropopause height (TH); (3) such a TH decrease tends to cause a change in the relative amounts of ozone–poor tropospheric and ozone–rich stratospheric air in the profile, which increases the partial column ozone in the UTLS and hence contributes to the TP TCO increase*”.

2. Lines 38-39: How a “decrease in the tropopause height” tends to “replace ozone-poor tropospheric air by ozone-rich stratospheric air in the UTLS”? Not clear. Revise.

The fact is that 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. Our Figures 6e-6f show that the TH decrease corresponds to the positive partial column ozone anomaly in the UTLS region, and vice versa for the TH increase. The TH decreases suggest that ozone–poor tropospheric air will be replaced in the profile by ozone–rich stratospheric air, which is supported by many studies (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). We have revised in [Lines 31-34]: "……*such a TH decrease tends to cause a change in the relative amounts of ozone–poor tropospheric and ozone–rich stratospheric air in the profile, which increases the partial column ozone in the UTLS and hence contributes to the TP TCO increase*".

3. Lines 42-45: But if the two phases have effects of opposite signs, and both phases will increase in frequency under a global-warming scenario (also, which one?), wouldn't be the final change almost null? Explain better.

We have deleted it and revised our implications as shown in [Lines 35-37]: "*This work provides a systematic understanding of the influence of ENSO on ozone over the TP, which have implications for a better understanding of factors controlling the interannual variability of ozone*".

4. Lines 51-53: How is the "clean air" connected with "strong surface solar ultraviolet (UV) radiation"? Explain better.

We apologise for this unclear sentence. We mean air that has a low concentration of aerosols. According to the Aerosol Robotic Network-based studies (e.g. Pokharel et al., 2019), the clean air corresponds to low aerosol optical depth. Since aerosol optical depth represent how much direct sunlight is prevented from reaching the ground by aerosol particles, the clean air over the TP corresponds to the strong sunlight and surface solar UV radiation (Pokharel et al., 2019). We have revised it in [Lines 45–46]: "*……clean air with low aerosol optical depth (Ahrens and Samson, 2011; Pokharel et al., 2019), the TP experiences strong sunlight and surface solar ultraviolet (UV) radiation……*".

5. Line 82: Still not clear, consider adding the number of events.

Sorry for this unclear sentence. We have added in [Line 73]: "……*limited ENSO events (4 El Niño, 3 La Niña)*……".

6. Lines 151-152: Why do you run simulations for the 1950-2022 period if the overlapping period is only 1979-2021. Please explain.

Good point. The model's initial simulations are unreliable as the model attempts to stabilize, which is the 'spin up' period (e.g. Birner et al., 2020). The selected overlapping period (1979-2021) could avoid the 'spin up' period of model. We have revised in [Lines 132-134]: "*The overlapping period between model and observations (i.e. 1979–2021) is used for analysis*".

7. Lines 154-155: The identification of the tropopause according to WMO is not a statistical method. Revise.

Sorry for this. We have removed the first sentence of section 2.3 [Line 136]: "*~~Several statistical methods~~……*".

8. Lines 158-161: 1) the composite analysis of what? 2) the statistical significance of what? 3) not clear how the two-tailed t-test can provide hints about the significance of the correlation.

To make it clear, more details have been added into revised manuscript, shown as follows:

1) [Lines 151–152]: *"……we perform composite analyses of ozone, SST, geopotential height, tropopause height, and air temperature during El Niño and La Niña events……*".

2) [Lines 154–155]: "*The statistical significance of composite is tested by the two–tailed Student's t–test (i.e. Kiladis and Diaz, 1989; von Storch and Zwiers, 1999)"*.

3) Based on the WMO's technical note (WMO, 1966) and statistical book (von Storch and Zwiers, 1999), the correlation follows Student's *t* distribution with effective number (N^{eff}). Therefore, the two-tailed *t*-test can provide some information about the significance of the correlation. We have added in [Line 146]: "……*where* r_{XY} *is correlation coefficient between two sampled time series (X and Y), and t value of* r_{XY} *follows Student's t distribution with* N^{eff}".

9. Lines 166-177: Also these methods are not statistical. Revise.

Yes. We have removed the first sentence of section 2.3 [Line 136]. Please see the response to *Specific comment 7.*

10. Lines 183-184: Again, it is not clear how the t-test can be used to infer about the statistical significance of the correlation.

We apologise for still not making this clear. We have now added more details on *t*-test and its statistical significance into revised manuscript. [Lines 141–149]: "*The statistical significance of the correlation between two auto–correlated time series is calculated using the two–tailed Student's t–test and the effective number (*N^{eff}*) of degrees of freedom (WMO, 1966; von Storch and Zwiers, 1999; Pyper and Peterman, 1998; Li et al., 2013), as given by the following approximation:*

$$t = r_{XY}\sqrt{\frac{N^{eff}}{1-r_{XY}^{2}}}$$

$$\frac{1}{N^{eff}} \approx \frac{1}{N} + \frac{2}{N}\sum_{j=1}^{N}\frac{N-j}{N}\rho_{XX}(j)\rho_{YY}(j) \qquad (1)$$

where r_{XY} is correlation coefficient between two sampled time series (X and Y), and t value of r_{XY} follows Student's t distribution with N^{eff}; N is the sample size, and ρ_{XX} and ρ_{YY} are the autocorrelations of two sampled time series, X and Y, respectively, at time lag j. Based on the two–tailed Student's t–test, the r_{XY} can be tested for statistical significance by solving for t in equation (1) and comparing this with the t value at confidence level and N^{eff}".

11. Lines 179-191: The consideration of only the correlation coefficients and their statistical significance (provided it is explained how the statistical significance of the t-test can provide indications on the correlation, which is not the case as noted previously) means that you are evaluating only that TOMCAT and C3S present the same time pattern in the (seasonal) TCO anomalies, while you are not saying anything on the presence of biases. Also, it would be interesting to evaluate the reason why the correlation is significantly lower (higher) in some particular seasons.

Thank you. Our responses to this comment can be listed as follows:

1) Since our results focus on the impact of ENSO on TP TCO variability from DJF to MAM, the high correlation (above 0.95, Figure 1) of TP TCO between TOMCAT and C3S data gives us confidence that the TOMCAT is able to capture the observed variability in TP TCO. We can thus use it to investigate the impact of ENSO on the TP TCO variability.

2) We agree that there are biases between C3S data and TOMCAT results. We have discussed the biases in first revised version as shown in [Lines 206–208 of the new revised manuscript]: "*These biases of TOMCAT simulation are likely due to (1) the incomplete representation of complex atmospheric process in TOMCAT, or (2) the uncertainties in TOMCAT's meteorology (ERA5 reanalysis scheme) (Mitchell et al., 2020; Dhomse et al., 2021)*".

3) **Some discussion about lower correlation.** Figure 1 shows relatively low correlation coefficients between C3S data and TOMCAT simulation from JJA to SON (correlations range from 0.65 to 0.8). We plot the time series of TP TCO anomaly averages for C3S and TOMCAT from JJA to SON (Figure A2). Figure A2 shows that TOMCAT performs reasonably well since 2014, but TOMCAT does not match C3S data well during the periods 1979-1986 and 2008-2013, and for the year 1995. TOMCAT is not a perfect model and its relatively low correlation with C3S is likely due to the convection parameterization. Since the convection parameterization simplifies atmospheric convective processes (e.g. Wu et al., 2011), it may affect the simulated tracer transport results. Given that TP convection is relatively strong from JJA to SON (Zhao et al., 2018),

this may cause more biases in TOMCAT. As the convection is weak from DJF to MAM (Zhao et al., 2018), TOMCAT performs reasonably well and its correlations with C3S are above 0.95.

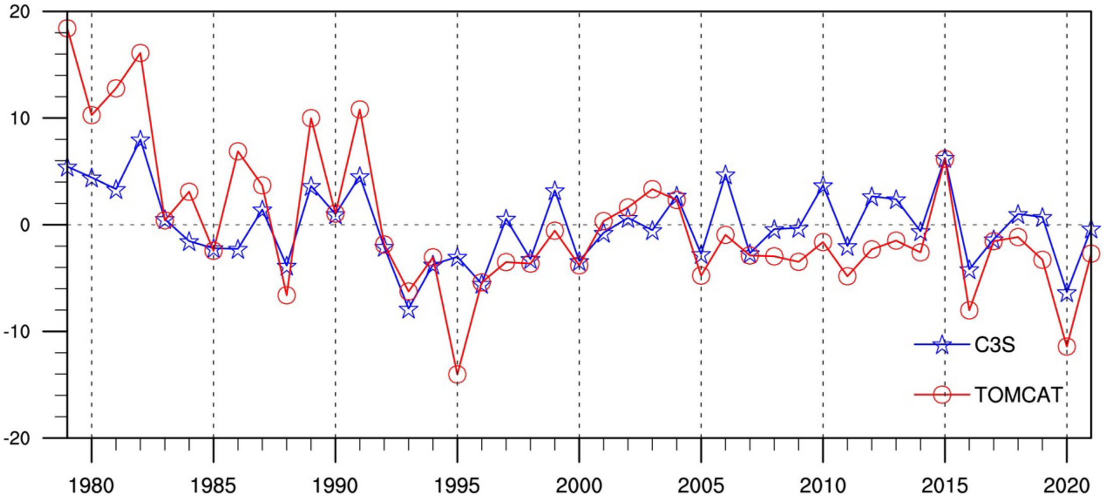


Figure A2: Time series of TCO (DU) anomaly averages over the TP for C3S data (blue) and TOMCAT result (red) from JJA to SON.

12. Lines 217-220: These details are more suitable for other sections.

Good point. We have moved the QBO index to section 2.2 [Lines 118–119]. In addition, its download link has been moved to Data Availability [Lines 452–453].

13. Lines 242-244: Shouldn't these details and methods be presented in the methods section?

Yes, a good point. We have moved these details and Tables 1-2 into the methods section. [Lines 155–165]: *"……The persistent ENSO events are based on the definition of NOAA Climate Prediction Center and our lead–lagged correlation results. We identify persistent El Niño (La Niña) events if their anomalous Niño 3.4 index is greater (less) than 0.5 K (–0.5 K) from winter (December–January–February; DJF) to spring (March–April–May; MAM). There are 7 and 9 events of persistent El Niño and La Niña (**Tables 1–2**), respectively……*".

14. Lines 320-391: Still not much clear the link between ENSO and change in TH (the link between TH and O3 content is instead straightforward). This improved explanation should be added to the conclusions and also in the abstract.

The improved explanation has been added into the conclusions and abstract in the revised manuscript.

Conclusion [Lines 411–426]: “*Regarding the El Niño events, its linkage with TP TCO is as follows: El Niño → negative upper–level geopotential height anomaly → thickness decrease → reduced tropospheric temperature → TH decrease → TCO increase, where the arrows show the cause-and-effect relationships. It is suggested that El Niño can trigger the TP TCO change via the following processes. Firstly, the El Niño events tend to exert the negative upper–level geopotential height anomaly (**Figure 7**) via the El Niño teleconnection and land-sea temperature contrast associated with El Niño, thus leading to the decreasing air thickness (**Figures 8a–8b**) based on equation (2) and previous studies (e.g. Wallace et al., 1996; Sun et al., 2017). Secondly, according to equation (3), the thickness decrease could reduce the tropospheric temperature over the TP (**Figures 8c–8d**), which further induces a decrease of TH (**Figure 6**) in terms of the tropopause definition of WMO (1957) and our results (**Figure 9**). Thirdly, such a TH decrease tends to cause a change in the relative amounts of ozone–poor tropospheric and ozone–rich stratospheric air in the profile, which increases the partial column ozone in the UTLS (**Figures 4 and 6**) and thus contributes to the TCO increase (**Figure 3**).The linkage between La Niña events and TP TCO as well as its associated processes resembles the El Niño events, except with anomalies of opposite sign*”.

Abstract is in [Lines 28–34]. Please see the responses to *Specific comment 1*.

15. Line 425: The statistical significance does not provide any indication about the presence or absence of the spread.

Yes, you are correct. The *p* value is used to evaluate the statistical significance of correlation relationship between ENSO and Thickness. We have revised the sentence. [Lines 378–379]: “*The relationship is significant ($p < 0.01$ or above the 99% confidence level), meaning the changes of ozone during the majority of ENSO events are coherent with the composite anomalies (**Figure 8**)*”.

16. Figure 9: 1) the correlation coefficient between change in thickness is not high; 2) there are some events for which the change in thickness is very limited

Our responses to this comment can be listed as follows:

1) Correlation coefficients are -0.56 and -0.85 in Figure 9. Many studies show that the correlation coefficient is high when its absolute value is above about 0.55. For example, correlation analyses in Trenberth (1975), Thompson and Wallace (1998), Mishra et al. (2011), Trenberth et al. (2015), and Zhang et al. (2014).

2) Yes, we agree. The results of significant correlation coefficient ($p < 0.01$) reveal that there is a robust linkage between ENSO and thickness. The fact is that ENSO can explain a part of total variability of thickness. There may be other factors impacting thickness. We have modified a caveat in the discussion to show the limitation and indication of Figure 9.

[Lines 433–439]: *“Although **Figure 9** is in good agreement with our study and shows that there are significant correlations between samples of ENSO events and air thickness as well as TH, it is also apparent a few samples deviate from the regression line and have the limited change. This implies that in addition to ENSO, there may be other factors contributing to the air thickness and TH variability and thus contributing to the TCO variation. Recently, Duan et al (2023) stated that the tropical Indian Ocean SSTA could cause a vertical shift of the ozone profile over the TP and thus contribute to the TCO variation……*”.

Technical comments

1. Lines 15-16: change “local ozone in the stratosphere” to “local stratospheric ozone concentration”.

Done.

2. Lines 19-20: Change “that there exists a positive correlation..” to “the existence of positive correlation..”

Changed.

3. Line 34: Change “which is the …” to “i.e. in the upper troposphere and lower stratosphere regions.”

Done.

4. Line 38: Change “decrease of” to “decrease in”.

Changed.

5. Line 49: Change “dominating” to “driving”.

Revised.

6. Line 55: Add “concentration variability” after “ozone”.

Added.

7. Line 67: Explain what is “SAH”.

“South Asian high” is now added.

8. Line 75: Change “on ENSO..” to “about ENSO..”

Changed.

9. Lines 78-79: Change “considering the major ozone production in the tropics…” to “as those two regions correspond to the highest production (tropics) and depletion (poles) on Earth.”

Changed.

10. Lines 99-137: the links and detailed information on the access date are not suitable for the main text, but need to be included in the reference (or data availability) sections. In the main text, following a more suitable format for references. Revise.

Revised.

11. Line 124: You mean “tropopause height”?

Yes, we have revised.

12. Line 136: Delete “that”.

Deleted.

13. Lines 148-150: Change “and calculates” to “and was used to calculate…”

Changed.

14. Lines 156-157: Change “…to find out during which periods there is a significant response…” to “the months when there is a …”

Changed.

15. Line 183 and 446: Change “strong” to “high”.

Changed.

16. Line 198: Change “lag-lead” to “lead-lagged”.

Changed.

17. Line 200: This sentence is not clear. Revise.

We apologise for this. This sentence is consistent with caption of Figure 2. We have deleted it.

18. Line 217: Change “then perform …” to “then perform lagged-lead correlation, shown in Figure 2a.”

Changed.

19. Lines 236-240: Rephase: “a) Lagged-lead correlation … b) same as a), but without considering the QBO signal on the TP TCO.

Rephrased.

20. Lines 242-244: The sentence is not clear, rephrase.

Rephrased, please see [Lines 155–158]

21. Line 245: Remove “the”.

Removed.

22. Lines 247-248: Remove such details about the identification from the caption.

Removed.

23. Line 255-257: Same as noted previously about the links and details about access date.

Revised.

24. Line 268: Change “in terms of” to “as evaluated in the”

Changed.

25. Line 269: Change “composited” to “composite”.

Changed.

26. Line 274: Change “to” to “until”

Changed.

27. Line 287: Change “of” to “in”

Changed.

28. Line 426: Delete “in” and change “composited” to “composite”.

Deleted and changed.

29. Line 451: Change “lead” to “lagged-lead”.

Changed.

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