Response to the Referees #1-2's comments on "The impact of El Niño–Southern Oscillation on the total column ozone over the Tibetan Plateau" (egusphere-2023-1452)

We thank Referees #1-2 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*).

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

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

General comments

This second revision of the paper successfully improved the quality of the paper, better clarifying several points that remained obscure after the first revision. However, there are some remaining issues that deserve attention. First of all, the use of correlation coefficients to explain causation, which is absolutely not enough. As I pointed out previously, the correlation coefficients actually indicate the presence of a similar time pattern in the two variables, but do not tell anything about the cause-effect relationship. Please have a look at Correlation vs Causation | Introduction to Statistics | JMP and the collection of spurious correlations from Tyler Vigen Spurious Correlations (tylervigen.com) Considering the methodology adopted here, it may be sufficient to point out this drawback and consider the correlation as a possible indication of a cause-effect relationship which needs to be demonstrated with other methods.

We thank again for the reviewer's comments and suggestions. We had improved our abstract and conclusion to infer causation. 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. We also had a caveat of correlation analysis in the first and second revised version [Lines 417–421].

To further verify our statistical results, we design and perform a series of model experiments to isolate the influence of ENSO. Since many studies has used Community Atmosphere Model version 4 (CAM4) developed by NCAR to isolate the SST–forced responses (e.g. Neale et al., 2013; Warner et al., 2020; Pausata et al., 2023), we will use CAM4 to support our findings. CAM4 is the atmospheric component of the Community Earth System Model (CESM). CAM4 has a horizontal resolution of 1.9° (latitude) × 2.5° (longitude) and 26 vertical levels. Three experiments are described in Table A1, all of which are same, but different SST forcings. The experiments were each run for 30 years, with the first 5 years excluded as a spin–up period. The remaining 25 years were used for the analysis.

As the tropopause height (TH) variability plays a key role in our potential mechanism, we display in Figure A1 the TH responses to El Niño and La Niña, averaged from December to May, when the response is significant (Figure 2 in manuscript). Figure A1 shows that El Niño (La Niña) generally correspond to a positive (negative) tropopause pressure differences over the almost the whole TP, which is in good agreement with the pattern of composite associated with El Niño (La Niña) events (Figure 6a–6b in manuscript). Note that the simulated intensity of tropopause pressure is stronger than that of composite in observations, which may be due to the model parameterization scheme over the TP is not perfect. Nevertheless, these simulations do support our statistical results.

Table A1 Description of experiments.

Experiments	Description
R0	Control run, using case F_2000. The solar forcing, carbon dioxide, ozone concentration, and aerosol are fixed at their level of 2000. Prescribed SST forcing used climatological present-day SST provided by NCAR.
R1	El Niño sensitive run, same as R0, but with SST anomalies (Figure 7a) added in Pacific (30°S-30°N, 120°E-80°W) from December to May.
R2	La Niña sensitive run, same as R0, but with SST anomalies (Figure 7b) added in Pacific (30°S-30°N, 120°E-80°W) from December to May.

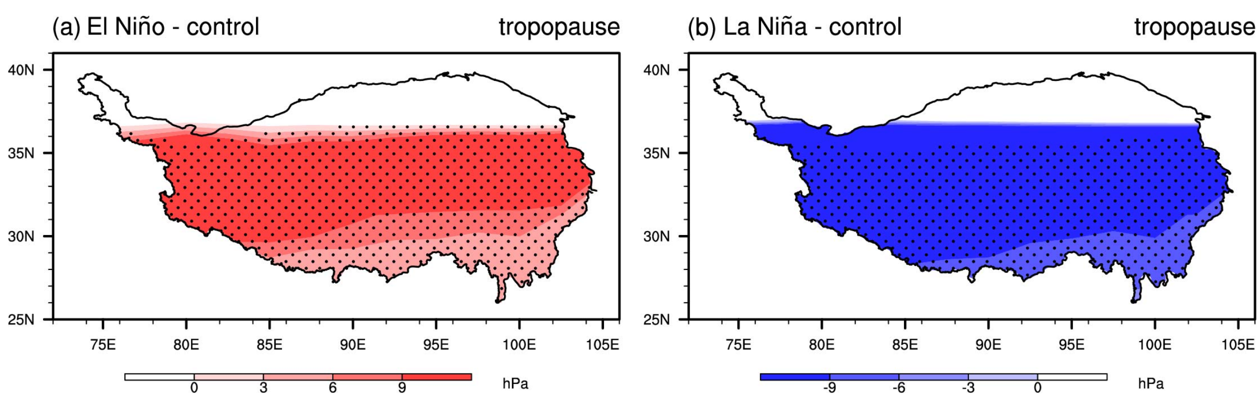

Figure A1: Differences in tropopause height (hPa) (a) between the El Niño response of experiments R1–R0 and (b) La Niña response of experiments R2–R0. The differences over the dotted regions are statistical significance at the 90% confidence level. The black lines represent the boundary of the TP.

An additional important note is that the authors analyse the differences between the mean of the events and the climate average, without considering: 1) whether the calculated differences are statistically significant; 2) the deviations around the means. The consideration of only the average values without inclusion of the variability around the mean could potentially mask the fact that the events and the climatological average could in reality belong to the same distribution; in addition, it is well known that the arithmetic mean is a parameter which is not resistant nor robust, which means that the presence of outliers could dramatically affect its value, and are not good if the population distribution is not normal. Considering these drawbacks and comments, my opinion is that the paper needs new major revisions before it can be accepted for publication.

The calculated differences are statistically significant, please see the following response (6th ***Specific comment***).

The deviations have been considered, please see the following responses (7th – 8th ***Specific comment***).

The composites associated with Figures 3–8 are all tested by the *t*–test, and its statistical significance indicate our results are significantly different from climatological average. Although there are some outliers, the scatterplot of Figure 9 shows most El Niño and La Niña events are coherent with composite results.

Specific comments

1. Lines 63-65: ENSO is a coupled climate phenomenon, involving changes not only in the ocean but also in the atmosphere which are not described here.

Revised. [Lines 57–59]: "*ENSO represents a periodic fluctuation in the tropical Pacific sea surface temperature (oceanic part: El Niño) and sea level pressure of the overlying atmosphere (atmospheric part: Southern Oscillation) during the warm (El Niño) and cold phase (La Niña)*".

2. Lines 112-115: This means that you are describing just the oceanic branch.

The Niño 3.4 index we used can measure ENSO, including its oceanic and atmospheric branches (e.g. Trenberth, 1997).

3. Lines 197-200 and previous review: the correlation coefficient is not indicative of a cause-effect relationship. Or, put in another way, "correlation is not causation". See: https://www.jmp.com/en_au/statistics-knowledge-portal/what-is-correlation/correlation-vs-causation.html So, I would suggest rephrasing or improving the analysis to infer causation.

Yes. In the second revision, the context had been improved to infer causation as shown in [Lines 194–196]: "……*response of TCO over the TP to ENSO may extend from winter of ENSO's mature phase to spring*……". In addition, we had added a caveat of correlation analysis in the second revision [Lines 417–421]. Please see more responses to ***General comment***.

4. Figure 2: I think the Figure needs better discussion and presentation, as: 1) it is presented as lagged correlation, but where is the lag? 2) the correlation is never higher than 0.40 (not high). Also, I do not understand why the correlation decreases without QBO.

To make it clear, more responses are shown as follows:

1) In the top X-axis, positive leads indicate that ENSO is leading or TP TCO is lagging. We have added it into Figure 2 caption [Line 217].

2) After removing the ENSO signal, there is no significant TCO anomaly over the whole TP during El Niño and La Niña years for C3S dataset and TOMCAT simulation (Figure A1 in the second response). Comparing the composite analyses of TP TCO with and without ENSO signal, it is further suggested that ENSO has a potential influence on TP TCO although their correlation is not very high. This is similar to the correlation between ENSO and monsoon. For example, ENSO plays a vital role in the American monsoon system although their correlation is lower than 0.4 (e.g. Arias et al., 2015).

3) The correlation without QBO signal (Figure 2b) is stronger than raw correlation (Figure 2a), which may be related to exclude interference of QBO signal.

5. Figure 3: The spatial pattern and also the values of anomalies of C3S and TOMCAT are consistently different. This needs to be better discussed in the text.

Good point. We have added the discussion into the revision. [Lines 224–228]: "*Although the spatial pattern and also the values of anomalies of C3S and TOMCAT are consistently different (**Figure 3**) due to the model's biases (Dhomse et al., 2021), the El Niño (La Niña) events correspond to the significantly positive (negative) TCO anomalies over the whole TP in both the C3S dataset and TOMCAT results (**Figure 3**). This result is consistent with that of correlation coefficients (**Figure 2**)*……".

6. Lines 273-280 and Figure 5: Are the differences statistically significant? The plots do not show very large differences, and the reader might wonder whether they are statistically significant. Also, since composite means are plotted, it would be needed to associate standard deviations / errors to the mean to be consistent (the difference could fall within the deviation range from the climate mean).

Yes, the differences are statistically significant. Figure 5 is identical to Figure 4 (Fig 4 → composite percentage change of ozone profile; Fig 5 → composite of ozone profile). We had added statistically significant and standard deviation (SD) into Figure 4 in the first revision.

7. Figure 6: Same as above for Figure 5 as for the climate mean lines.

We have modified the Figure 6 in the new revision. Green lines with standard deviation (shaded areas) indicate the composite tropopause, and thick green lines indicate the composite tropopause which exceed the 90% confidence level.

8. Lines 354-356: Same as above as for the calculation of only means without considering a deviation around the mean value.

Based on Figure 8, Figure A2 shows the area-averaged values with standard deviation (vertical bars) of Tthickness and Ttroposphere_mean over the whole TP. We have added this Figure into Supplementary Material.

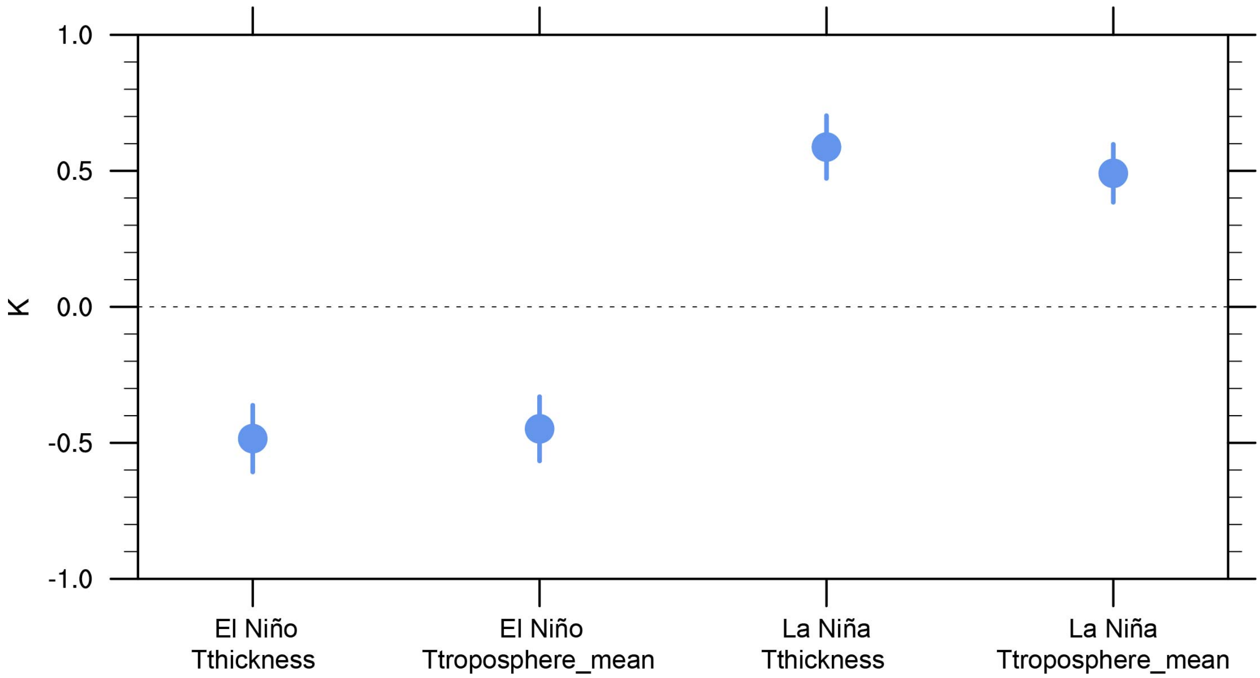

Figure A2: The circles represent the area–averaged values of Tthickness and Ttroposphere_mean over the whole TP based on Figure 8. The vertical bars represent standard deviation.

9. Figure 9: Again, only mean values are considered in the analysis.

Figure 9 is scatterplot, and it mainly focuses on the relationship between ENSO events and air thickness as well as tropopause rather than their mean values. Please see the context as shown in [Lines 356–371].

Technical comments

1. Lines 34-37: The two sentences are somehow a repetition, I think a rephrase could improve the readability.

Rephrased.

2. Line 64: change "warmer phase (El Niño) and colder phase (La Niña)" to " the warm (El Niño) and cold phase (La Niña)"

Changed.

3. Line 73: Add "a very limited number of" before "events"

Added

4. Lines 215-216: It is not clear which results show this minor impact of QBO. Please explain better, perhaps moving sentences.

Deleted.

5. Line 255 and 278: Which biases cause this disagreement? Explain.

We had explained the biases in [Lines 189–191].

6. Lines 264-265: It is not clear which are the shaded regions, as the colours refer to the color scale.

Changed. [Lines 244-245]: "*Coloured regions indicate statistical significance……*"

7. Line 273: Delete "the" after "Such".

Deleted.

8. Line 283: Change "of" to "in"

Changed.

9. Lines 411-415: This scheme with arrows could be brilliant for an oral presentation over a slide, but not so much for a paper. Please rephrase with complete sentences.

OK. It has been deleted.

References

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

General comments

The manuscript of “The impact of El Niño–Southern Oscillation on the total column ozone over the Tibetan Plateau” by Yang Li et al. focuses on the effect of the ENSO on total column ozone (TCO) above the Tibetan Plateau (TP). Through analysis of the aggregated long-term satellite data C3S, the chemical transport model TOMCAT, and the water vapor and ozone dataset SWOOSH, the authors present statistical significant relations of positive TCO anomalies above the TP during El Niño and vice versa for La Niña events. These anomalies are robustly found in all presented datasets.
This study is definitely relevant and suits the scope of ACP well and is a welcome addition for the atmospheric community. The manuscript itself is mostly well written and understandable. However, there are parts, that are less well described and early conclusions that cannot be followed in the current state of the article. Hence, a major revision of this article are needed before a recommendation for publishing can be made.

Many thanks for the positive evaluation and the suggestions to improve the paper. We have revised our manuscript based on your comments and suggestion.

In particular, the authors only look at correlations of different parameters and jump to the conclusion of a causation. The whole mechanism of the TCO increase described in the conclusion is not well supported by the findings of the study and could be argued for in different order as well. The ENSO is leading the TCO anomaly but it is not clear if the cooling of the troposphere or the lowered geopotential height of the 150 hPa level is the next step in the mechanism. Since only the correlations are shown, this conclusion cannot be drawn.

We had improved our abstract and conclusion to infer causation. We also had added a caveat of correlation analysis in the second revision [Lines 417–421].

To verify this potential mechanism, we design and perform a series of model experiments to isolate the influence of ENSO. Since many studies has used Community Atmosphere Model version 4 (CAM4) developed by NCAR to isolate the SST–forced responses (e.g. Neale et al., 2013; Warner et al., 2020; Pausata et al., 2023), we will use CAM4 to support our findings. CAM4 is the atmospheric component of the Community Earth System Model (CESM). CAM4 has a horizontal resolution of 1.9° (latitude) × 2.5° (longitude) and 26 vertical levels. Three experiments are described in Table B1, all of which are same, but different SST forcings. The experiments were each run for 30 years, with the first 5 years excluded as a spin–up period. The remaining 25 years were used for the analysis.
As the cooling/warming troposphere is accompanied by the tropopause height (TH) variability and the TH plays a key role in our potential mechanism, we display in Figure B1 the TH responses to El Niño and La Niña, averaged from December to May, when the response is significant (Figure 2 in manuscript). Figure B1 shows that El Niño (La Niña) generally correspond to a positive

(negative) tropopause pressure differences over the almost the whole TP, which is in good agreement with the pattern of composite associated with El Niño (La Niña) events (Figure 6a–6b in manuscript). Note that the simulated intensity of tropopause pressure is stronger than that of composite in observations, which may be due to the model parameterization scheme over the TP is not perfect. Nevertheless, these simulations do support our statistical results.

Table B1 Description of experiments.

Experiments	Description
R0	Control run, using case F_2000. The solar forcing, carbon dioxide, ozone concentration, and aerosol are fixed at their level of 2000. Prescribed SST forcing used climatological present-day SST provided by NCAR.
R1	El Niño sensitive run, same as R0, but with SST anomalies (Figure 7a) added in Pacific (30°S-30°N, 120°E-80°W) from December to May.
R2	La Niña sensitive run, same as R0, but with SST anomalies (Figure 7b) added in Pacific (30°S-30°N, 120°E-80°W) from December to May.

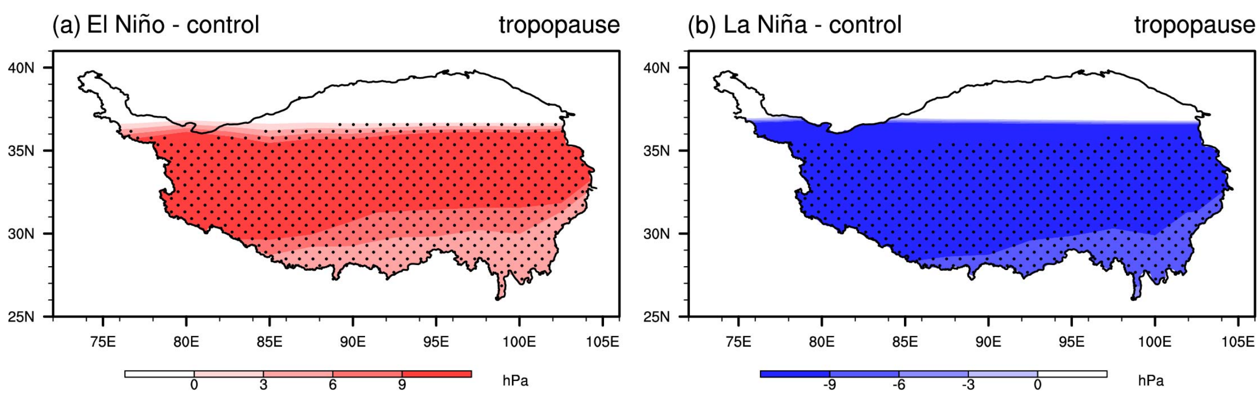

Figure B1: Differences in tropopause height (hPa) (a) between the El Niño response of experiments R1–R0 and (b) La Niña response of experiments R2–R0. The differences over the dotted regions are statistical significance at the 90% confidence level. The black lines represent the boundary of the TP.

Furthermore, the increase of the TCO is argued by the reduction in tropospheric height and a subsequent "change in the relative amounts of ozone–poor tropospheric and ozone–rich stratospheric air in the profile". While this is true for the relative amounts of air, it is not necessarily for the TCO. The TCO can only increase if there is an influx of stratospheric, ozone-rich air from other regions. This is not talked about although it is the center point of this study.

In general, the authors should either rephrase their claims or increase their evidence for the presented mechanism. In the current state, the stated causation is not evident.

Following are specific and technical comments with citations from the manuscript given in italics.

Based on previous studies (e.g. Salby and Callaghan 1993; Appenzeller et al., 2000; Tian et al., 2007, 2008; Zhang et al., 2014, 2015), the increasing TH corresponds to the upward motion, which is accompanied by mass convergence at lower troposphere; this would carry ozone-poor tropospheric air into the UTLS region and hence decrease the TCO. For the decreasing TH, it

favours the downward motion and convergence at lower stratosphere, which could bring ozone-rich stratospheric air into the UTLS region, thereby giving rise to TCO increase (e.g. Salby and Callaghan 1993; Appenzeller et al., 2000; Tian et al., 2007, 2008; Zhang et al., 2014, 2015).
We have rephrased context as shown in Section 3.2 [Lines 273–276]: "*Therefore, the increasing (decreasing) TH will tend to carry ozone-poor (ozone-rich) tropospheric (stratospheric) air into the UTLS region, and thus decrease (increase) the partial column ozone, which in turn contributes to the TCO decrease (increase)*".

Specific comments

1. l 57 ff: There is no mention about the atmospheric part of the ENSO, i.e., the SO part. Add a sentence describing this as well.

Revised. [Lines 57–59]: "*ENSO represents a periodic fluctuation in the tropical Pacific sea surface temperature (oceanic part: El Niño) and sea level pressure of the overlying atmosphere (atmospheric part: Southern Oscillation) during the warm (El Niño) and cold phase (La Niña)*".

2. l 99: how many vertical levels does your data span between 1000 and 0.01 hPa?

Added. [Lines 100–101]: "…… from 1000 to 0.01 hPa (137 vertical levels)".

3. l 122:which is calculated according to cross correlation function (Chatfield, 1982): probably an article missing (a or the?), but the cross correlation function should be described by a bit more detail. Or the sentence should be rephrased for better understandability.

Rephrased. [Lines 124–126]: "……*which is calculated according to the cross correlation function (e.g. Trenberth et al., 2002). The significant cross correlation between ENSO(t) and TCO(t+τ) indicates that ENSO may influence the TCO when ENSO leads TCO at a lead of τ*".

4. l 224: ±1.2% percentage change (i.e., anomaly divided by climate mean) of TP TCO You stated that your dataset has an accuracy of about 2%, which would render this change to be within the expected error if found in an individual case. Please comment on the this discrepancy within the text. Since you use composite events, the errors are canceling to some extent. Do you have a feeling to what extent?

From the perspective of TCO, Xie et al. (2014) focused on the impacts of ENSO on global ozone change using ERA-Interim data, and their percentage change over the latitude-longitude TP domain (their Figure 6a) is consistent with ours. Because of similar change between our results and previous study, we feel the errors will be cancelled to some extent using composite although we are not sure what extent. To be clearer, we modified the percentage change to TCO anomaly as shown in [Lines 228]: "……*about ±3.5 DU of TP TCO anomaly* ……"

From the perspective of ozone profile, Figure 4 shows that the ENSO events correspond to about ±6% percentage change at 200-70 hPa, which is larger than the systematic error (below 2%). We have added this into [Lines 251]: "……*about ±6%*......".

5. l 225 ff: To further clarify the influence of ENSO on TP TCO, we use 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). As it is, this section gives no new information since it basically reads as: if we remove the linear relation, we find no longer a linear relation. Please describe how you removed the ENSO signal. This should be a physically justified approach for the separation. If it is actually a regression separation, remove this part.

We used regression method to remove the ENSO signal, and we have removed this part.

6. Fig. 3: There is a shaded region mentioned for the stat. significance, but not shown. Change this to state something like: 'There is no region, where the anomaly is statistically significant beyond the 90% confidence level.' in the caption.

Sorry for this unclear. The caption has been revised as shown in [Lines 243–244]: "*Coloured regions indicate statistical significance at the 90% confidence level*……".

7. l 243 ff: although the altitudes of 100–50 hPa agree with your vertical shift hypothesis, the Ozone profiles between 200–100 hPa show a different slope for El Niño and La Niña. This might not only be related to a vertical shift but a compression/stretching of the profile for Niño and La Niña, respectively?

These sentences associated with Figure 4 depict the composite percentage change (%) of ozone profile rather than the raw ozone profile. Although the slopes of percentage change between 100–50 hPa and 200–100 hPa are different, Figure 5 shows the ozone profiles at these two levels all show the downward (upward) for El Niño (La Niña) events. Sorry for this unclear. We have revised the sentences as shown in [Lines 250–251]: "…...*increase (decrease) of ozone percentage change (about ±6%) at 200–70 hPa*……".

8. l 270 ff: Therefore, a decrease of tropopause height (TH) will tend to replace ozone–poor tropospheric air by ozone–rich stratospheric air in the UTLS region ... This would only be true, if there is horizontal flow of from surrounding areas towards the TP. In other words, a constant

Stratopause would be expected and/or an opposite TCO anomaly adjacent to the TP. The Ozone has to come from somewhere. Please add on this question for a more detailed description of this process. As it is right now, your point is not self-sufficient.

Please see the detailed response mentioned above (3rd ***General comment***).

9. l 331 f: That is, the tropospheric temperature will warm (cool) when the rising (falling) GH150 causes the increased (decreased) air column thickness. This sounds too much like a cause and consequence where only correlation is seen. Please rephrase this sentence accordingly.

Revised. [Lines 337-339]: "*That is, the increased (decreased) air column thickness associated with the rising (falling) GH150 favours the warming (cooling) tropospheric temperature.*"

10. l 339 f: According to equation (3), this implies that the El Niño (La Niña) events favour the decreased (increased) air thickness and thus contributes to the cooling (warming) tropospheric mean temperature (Figures 8). 'Contributes' is more than you can claim here, I would say it is 'associated with' since you only found the correlation.

Revised. [Lines 347]: "……*thus associated with*……".

11. l 351 f: ... there is a strong negative correlation (–0.56) between Niño 3.4 and temperature associated with air thickness. While it is very convincing that the air thickness is related to whether there is a El Niño or La Niña, the correlation to Niño 3.4 is not as convincing. Did you have a look at other indices and their correlation to the air thickness? And what about the non-ENSO events in the same periods, do they fall close to the center point in this diagram, or are they scattered on the vertical axis? Please comment on this in the text.

Good points! To make it clear, more responses are shown as follows:

1) In addition to Niño 3.4 index, Niño 3 index, which is calculated with SSTA in the area (5°S - 5°N, 90°W - 150°W), is another indicator for ENSO. The correlation coefficient between Niño 3 and temperature associated with air thickness is about –0.559 ($p < 0.01$), which is in good agreement with that of Niño 3.4 index. We have added this in [Lines 360-361]: "*Another ENSO index (Niño 3; area–averaged SSTA in 5°S–5°N, 90°W–150°W) has about the same correlation as Nino 3.4 index*".

2) We have added this in [Lines 361-363]: "*Meanwhile, the correlation coefficient between non–ENSO events (Niño 3.4 index is less than 0.5 K and greater than –0.5 K) and their corresponding temperature associated with air thickness is about –0.12 ($p > 0.1$), suggesting that there is no relationship between them*".

12. l 378 f: ...with and without ENSO signal... should be '...with and without QBO signal...' if I'm not mistaken.

Sorry for this typo. Yes, it is "*with and without QBO signal*", and it has been revised in [Lines 388–389].

13. l 393 ff: 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... See above. The partial column ozone will change for a fixed pressure interval, but for the TCO, there needs to be an influx (or source) of Ozone adjacent to the column. The process described here is not clear. The main question I'm left with is: where is the additional Ozone in the TCO stemming from?

Please see the detailed response mentioned above (3rd ***General comment***).

Technical comments

1. l 67: since the satellite era → during the satellite era

Revised.

2. l 104: of area averaged of SST anomalies (SSTA) → of area averaged SST anomalies (SSTA)

Revised.

3. l 104 f: consider adding a reference to the website here

We had added website in *Data availability* [Lines 429–430].

4. l 106 f: As the SWOOSH spans from 1984 to the present, its anomalies are with respect to the period 1984–2021. consider rephrasing this for better understanding

Rephrased.

5. l 131 f: In view of the fact that the relationship between the positive and negative ENSO phases may not be linear (An and Jin 2004), we consider El Niño and La Niña events should be analyzed separately. remove 'should be analyzed' or 'we consider'

Yes. We have removed '*should be analyzed'*.

6. l 187: presentation → representation

Changed.

7. sec 3.1: use lead-lagged (or lagged-lead if you prefer this) consistently in your text and captions

OK. We have modified text and caption.

8. l 247: remove Such

Modified.

9. l 250: remove , whose results are consistent with Figures 5a and 5d. Since its only a zoom it is not only consistent but identical. No need to clarify after stating it's a zoom.

Removed.

References

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