We would like to thank all reviewers for their helpful comments. Their ideas and suggestions have improved the manuscript. We have detailed the changes as best as possible in the response below, and were refer the reviewers to the diff.pdf version of the paper that shows all of the changes.

Reviewer #1 comment on "Variability of temperature and ozone in the upper troposphere and lower stratosphere from multi-satellite observations and reanalysis data" by Shangguan et. al.

Reviewer #1 (Comments to Author):
Review of: Variability of temperature and ozone in the upper troposphere and lower stratosphere from multi-satellite observations and reanalysis data. Thank you for the pleasure of reviewing this paper. It is well written (with only a couple of English corrections), well laid out and has very good graphics. I very much like the usage of various satellite data, reanalysis data and comparisons with models to show if how/where/when reanalysis data could be problematic for trend detection. The usage of a model with and without real time SST shows the role of dynamics and radiation upon the temperature and ozone variations over this albeit short period of 2002-2017. The great thing about GNSS-RO data is that it is unbiased and has been shown by several authors how its assimilation harmonizes the temperatures of the various reanalyses from ~2004 forward. Unfortunately, as the reanalyses migrate their temperatures toward the GNSS-RO values, any previous bias impacts the temperature trends from before to after the usage of GNSS-RO data. This word of caution is presented by the authors and can't be over emphasized.
I thought the authors do a great job presenting how the ozone and temperatures are interdependent and the roles of dynamics and radiation upon them. The ozone data sets used have both pros and cons. The conversion of number density to ozone mixing ratio is dependent upon the temperatures used. An erroneous trend in temperatures could impart an unwanted trend in ozone mixing ratio values. But that is a separate issue unrelated to the purpose of this paper.
Thank you very much for your very helpful comments. We have revised our manuscript accordingly and hope the manuscript have been considerably improved. Please see our point-to-point response as follows.
Reviewer comments are in black, following by our respective replies in blue.

Here are my line-by-line comments:

It is my understanding that GPS-RO is a particular type of radio occultation and that the more general Global Navigation Satellite System (GNSS-RO) should be used to cover all types of RO satellite systems.
Thank you very much for your remark. We have modified all the GPS-RO to GNSS-RO in the text.
Page 3, Line 7: Replace 'get' with 'be'.
It has been corrected.
Page 3, Line 14: Replace 'continues' with 'continuous'

Corrected.
Page 3, Line 21: Remove the 'a' in the phrase 'found decreasing ozone'
Updated.
Page 3, Line 25: Is 'LS' defined earlier in the paper, otherwise use 'lower stratosphere'
Thank you for your remark. We have replaced LS with the lower stratosphere.
Page 3, Line 26: Use 'increasing or declining'
Done.
Page 3, Line 30: Replace 'Although might be still problematic' with 'Although it might still be problematic'
Corrected.
Page 4, Line 6: Replace 'recorded' with 'record'
Done.
Page 4, Line 12: 'In Sect. 3 we compare'
Updated.
Page 4, Line 17: Replace 'Around one decade CHAMP' with 'Nearly one decade of CHAMP'
Thanks. We have updated this sentence as suggested.
Page 4, Line 19: Replace 'provides more than 10 times of' with 'providing more than 10 times the number of'
Yes, it has been done.
Page 4, Line 27: Replace 'can be already captured by single satellite' with 'has already been captured by a single satellite'
Thanks. We have revised this sentence as suggested.
Page 6, Line 12: 'qulaity' is misspelled 'quality'
Corrected.
Page 6, Line 15: Replace 'since' with 'beginning in'
We have done the correction according to your comment.
Page 7, Line 3: Replace 'has been proved for a better representation to the detailed'with 'has been proved to better represent the detailed'.
Done.
Page 7, Line 19: 'QBO coefficients'
Corrected.
Page 7, Line 20: 'a4' is the QBO30 coefficient, is there a missing solar term in equation1 with a coefficient a5?
We apologize for this mistake. Yes, 'a4' is the QBO30 coefficient. We have corrected this sentence in the revised manuscript.
Page 7, Line 30: 'between reanalyses and from the GPS-RO data.'
Corrected.
Page 9, Paragraph beginning at line 3: Does the transition and use of MLS temps affect the MERRA2 trends? How does MERRA2 perform after vs before the use of CHAMP in 2004?
According to previous studies (e.g., McCarty et al., 2016; Fujiwara et al., 2017), the MERRA2 only assimilated MLS temperature observations at and above 5 hPa. For this study, since we are focusing on the region below 10 hPa, the MERRA2 trends shown in this study should not be affected by the MLS temperatures. However, this effect should be considered while investigating temperature trends above 5 hPa.

The effect of the CHAMP to MERRA2, as introduced in MERRA2 on 15 July 2004 (McCarty et al., 2016), is not significant since the single CHAMP satellite has very limited number of observations.
Page 9, Line 31: 'MERRA2', Do you have a reason why ERA-I trends are 'flat'?
As shown in Figure 6(a) the ERA-I temperature anomalies from 2002 to mid-2006 are
highest compared to other data sets. According to Simmons et al. (2014), local degradation occurs near the sub-tropical tropopause whereas substantial amounts of warm-biased aircraft data are assimilated since 1999. After 2006, while large number of COSMIC data is assimilated, this warm bias disappeared. This led to less warming at 150 hPa in the tropical region represented by ERA-I.
Page 10, Line 29: 'estimated'
Corrected.
Page 10, Line 31: 'MERRA2'
Corrected.
Page 11, Line 1: 'At 10 hPa all the data sets'
Updated.
Page 11, Line 11: 'confirmed by Table 1'
Done.
Page 11, Line 28: 'it does not assimilate as many ozone'
Corrected.
Page 12, Line 20: 'which is the reason of the positive'
Done.
Page 12, Line 32: 'SST's (Figures 15b-c).'
Corrected.
Page 13, Line 3: 'less ozone in the tropical lower'
Done.
Page 13, Line 7: 'SST increases are asymmetric in the two'
We have done this update.
Page 13, Line 22: 'shows obvious improvements in reference to ERA-I'
Corrected.
Page 13, Line 23:'well known that are related to'
Done.
Page 13, Line 31: 'In contrast to the troposphere'
Done.
Page 14, Line 6: 'can be found for the two hemispheres'
Done.
Page 14, Line 13: 'supports'
Corrected.
Page 14, Line 17: Remove 'neither'
Done.
Figure 1: Label every other year on the X-axis; in the caption: 'between three reanalyses'
Thanks. We have updated the figure as well as the caption as suggested.
Figure 2+: Referring to previous figures should be capitalized: 'Same as Figure 1'
Thanks, it has been corrected.
Figure 4: 'The two missions obtained'

Done.
Figures 1,2,3,13. It is hard to distinguish the black lines from the blue lines. Could another color or a lighter shade of blue be use.
Thank you very much for your advices. We have changed the color in Figures 1, 2, 3,13.

References
McCarty, W., Coy, L., Gelaro, R., Huang, A., Merkova, D., Smith, E. B., Sienkiewicz, M., and K., W.: NASA Tech. Rep. NASA/TM{2016{104606, https://gmao.gsfc.nasa.gov/pubs/docs/McCarty885.pdf, 2016.
Fujiwara, M., Wright, J. S., Manney, G. L., Gray, L. J., Anstey, J., Birner, T., Davis, S., Gerber, E. P., Harvey, V. L., Hegglin, M. I., Homeyer, C. R., Knox, J. A., Kruger, K., Lambert, A., Long, C. S., Martineau, P., Molod, A., Monge-Sanz, B. ¨M., San- tee, M. L., Tegtmeier, S., Chabrillat, S., Tan, D. G. H., Jack- son, D. R., Polavarapu, S., Compo, G. P., Dragani, R., Ebisuzaki, W., Harada, Y., Kobayashi, C., McCarty, W., Onogi, K., Paw- son, S., Simmons, A., Wargan, K., Whitaker, J. S., and Zou, C.-Z.: Introduction to the SPARC Reanalysis Intercomparison Project (S-RIP) and overview of the reanalysis systems, At- mos. Chem. Phys., 17, 1417{1452, https://doi.org/10.5194/acp- 17-1417-2017, 2017.
Simmons, A. J., Poli, P., Dee, D. P., Berrisford, P., Hersbach, H., Kobayashi, S., and Peubey, C.: Estimating low-frequency variability and trends in atmospheric temperature using ERA-Interim, Quarterly Journal of the Royal Meteorological Society, 140,329-353, 2014.

Reviewer #2 (Comments to Author):

This paper uses temperature and ozone from satellite measurements and reanalysis products to estimate their variability and trends in the upper troposphere and lower stratosphere (UTLS). Trends are analyzed between 2002 and 2017, and multiple-linear regression model is applied to separate the influences of the Quasi-biennial Oscillation (QBO) and the El Nino Southern Oscillation (ENSO) from trends. In the context of the SPARC Reanalysis Intercomparison Project this paper is an important contribution to the literature. Unfortunately, this paper does not clearly motivate its objective and misses several marks scientifically. In particular, trend analyses over such a short time-period are suspect and (as the paper shows) inconsistent, making interpretation of these results difficult. Furthermore, connections between ozone and temperature are loosely implied in manuscript without detailed analysis, and the modeling results presented herein are not explained in depth. Finally, the paper is poorly written with grammatical and spelling mistakes throughout, making it very difficult to follow at numerous points. If major revisions are made to address these shortcomings, this paper will be a valuable contribution to the SPARC Reanalysis Intercomparison Project.

We thank the reviewer very much for the very constructive and useful comments and suggestions. We have revised the manuscript according to all the comments. Firstly, we have rewritten our introduction to explain our motivation clearly in the context of the SPARC Reanalysis Intercomparison Project. Secondly, we rechecked the significance of the trends by calculating the signal-to-noise ratio. Thirdly, we have made a correlation test between temperature and ozone time series to study the connection between ozone and temperature. We apologize for the grammatical and spelling mistakes and we have checked the whole text carefully and corrected the mistakes. We hope the reviewer could find the manuscript has been improved significantly.

Please see below our point-to-point response to all reviewers' comments and suggestions. Reviewer comments are in black, following by our respective replies in blue.

Major Comments:

1. This paper is challenging to read because it has significant grammatical errors
and spelling mistakes. Often sentences are difficult to parse without several readings, and these problems detract significantly from the scientific content of the paper. For
instance, in a part of the paper with an important physically-based discussion (the discussion of model results on pg. 13, line 1), the main sentence of the discussion is so confusing that the message being conveyed is lost. In another example, the primary sentence outlining the paper's goal (pg. 2, line 25) is choppy and unclear, blurring the paper's motivation. I've highlighted some of the more obvious problems in the line-by-line comments below, and at minimum these should be addressed. Preferably, the entire paper would be carefully edited to improve its readability and appropriately convey the authors' scientific findings.

Thank you very much for your comments. We are really sorry for so many grammatical errors and spelling mistakes in the text. We have modified the text according to your suggestions and edited the entire paper carefully. The introduction has been rewritten to explain our motivation clearly. More details can be found in our line-by-line response and the revised manuscript.

2. Because reanalysis products are combinations of observations and models to assimilate the data, it is disingenuous to consider their trends as directly related to observations. Furthermore, interpretation of reanalysis trends is complicated because the assimilation step brings in data which leads to discontinuities which will vary from place-to-place, time-to-time, and reanalysis-to-reanalysis. The authors themselves acknowledge this problem (pg. 2, line 31), but proceed with their analyses without quantifying how discontinuities affect their results. Reanalyses trend results presented here are suspect and must be interpreted with caution. Without significant changes to the trends analyses (some ideas to do this I suggest below), the authors should instead shift the main focus of their paper to the comparisons between the variabilities in the reanalysis and GPS products.

We totally agree with the reviewer that the reanalysis products are influenced by both observations and assimilation systems and should not be compared to observed trends directly. According to your suggestions, we have rewritten our introduction and shift the main focus of the paper to the comparisons between the variabilities in the reanalysis and GNSS products.

In addition, we corrected the temperature discontinuities around 2006 in the reanalysis by using a transfer function approach similar to Wargan et al., 2018. The corrected GNSS RO time series was used as a common baseline since it does not have significant discontinuities. Details of the bias correction for reanalysis temperatures can be seen in the supplementary information. The temperature trends from reanalysis data sets were recalculated and their significance was also rechecked using the signal-to-noise ratio.

3. The problem of interpreting trends from reanalysis is exacerbated by the very short time period considered in this study. A 15-year period (2002-2017) to calculate trends is quite short, and I suspect this contributes to one of the main results of this paper (Table 1), that trends vary in sign and significance depending on the region (except in the tropical middle stratosphere, 10hPa, where trends are more robust, but which is not the focus of this UTLS paper). By eye, the trends appear to be in agreement with one another (Figure 11) in the stratosphere, but there are clear distinctions which makes overall interpretation challenging. This is an inherent difficulty for the study, because GPS data does not extend earlier than 2002. The authors themselves note (citing Santer et al., 2017) that the trend assessment from such short periods can be strongly influenced by start/end years (see also Bandoro et al. 2017, Santer et al. 2011). Given how short the period of record is, without a detailed signal to noise study, is too early to make decisive or defensible claims about UTLS temperature trends in the 21st century. If this study was improved to include a signal-to-noise study which showed the trends are robust, the study results would be more compelling.

Thank you very much for the constructive comments. Yes, the 16-year period is relatively short to calculate trends and there is clear distinction between different data sets especially in regions with insignificant trends. According to your suggestion we have made a signal to noise study based on three 145-years CESM simulations. The CESM runs were integrated in a fully coupled mode with an interactive ocean for the time period 1955 to 2099. All anthropogenic forcing, e.g. GHGs and ODSs were fixed to values at the year 1960. The three simulations are slightly different with the natural forcing. The first run used observed solar irradiance, time varying volcanic aerosols and a nudged QBO, while the second run fixed the solar irradiance as a constant and the third run did not include a QBO. More details of the simulations can be seen in the supplementary information. The influences of solar cycle, volcanic aerosols and QBO were excluded by a multiple linear regression before the calculations of the background noise.

To assess the effect of seasonal and interannual variability on 16-year temperature trends, we fit linear trends to overlapping 192-month segments of the 1740-month in each of CESM runs. For maximally overlapping 192-month intervals (i.e., for overlap by all but one month), one simulation yields 1549 samples of 192-month trends. Following the method described by Bandoro et al. 2017 and Santer et al. 2011, we exclude the largest cooling or warming trends from our analysis and calculate the standard deviations of the 16-year trends (right panel in Fig.1). Note that the method used here is slightly different with that in Bandoro et al. 2017. We estimated the standard deviation of by different overlapping 16-year trends from the same model while they used a large ensemble of simulations with different models. The advantage of their approach is that the results are not model dependent. However, our results based on the CESM model should be helpful since it is one of the best models and has been widely used in UTLS studies.

The signal to noise ratios of 16-year GNSS RO temperature trends are shown in Fig.1 (left panel). Here we use the 90% and 95% significance level, which corresponds to a signal to noise ratio close to 1.65 and 1.96. Seen from Fig. 1, the areas with significant trends are smaller than that shown in Fig. 11 in the main text. However, there are still significant signals in the mid-latitudes of the upper troposphere, around the tropopause and in the southern hemisphere in the middle stratosphere. All the significant regions in Fig. 1 are actually the most important areas with strongest and significant trends in Fig. 11. This suggests that the significant trends shown in Fig. 11 are robust except that in the tropics whereas the standard deviation of the trends are the strongest.

To my understanding, the signal-to-noise ratio suggested by the reviewer and the significance test used in this manuscript are actually two methods to test the significance/robustness of the calculated trends. The main difference between the two methods is the way to estimate the standard deviation/noise. Since the standard deviation of the residuals of the linear fit has been widely used in trend analysis (e.g., Wigley et al., 2006), we would like to keep the significance test as it was in the manuscript. At the same time, we have put Fig. 1 in the supplementary and added some discussions correspondingly in the revised manuscript.

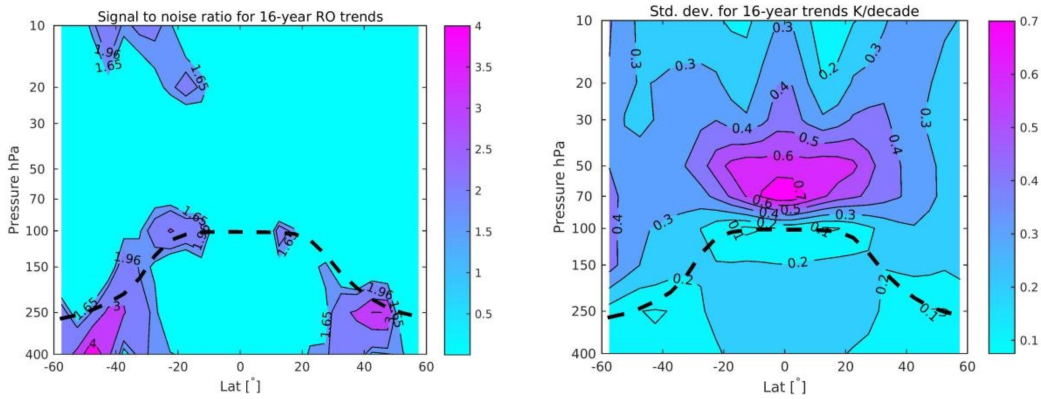

Figure 1: Signal to noise ratios (left) are estimated RO trends divided by the standard deviations of model trends (right), calculated using overlapping time series segment.

4. One of the main reasons short trend calculations here are challenging is because of biases early in the time period (2001-2006), as noted in the text and shown in Figures 1. These biases early in the period will drive trends in

the underlying data which will factor into the trends calculated with the MLR method. For instance, I can quickly estimate the following trends in the biases: @400hPa: +0.2 K/decade, @100hPa: +0.35 K/decade, @70hPa: +0.25 K/decade. Each of these is on the order of the trends found in Table 1 for those regions, making it very difficult to determine whether trends found to be "significant" are actually just trending because of early period biases. Table1 should be updated to include the trends in the biases (like the estimates above) for each product and region (or some similar analysis), and to directly with the calculated trends (e.g., this method is used to examine radiosonde trends in Wang et al. 2012). Where the bias trend is on the order of the product temperature trends, the robustness of those trends should be reconsidered.

Thank you for your suggestion. We tried to add the bias trends in table 1. However, there are too many numbers and hard to clearly show the important information. Therefore, we put the uncorrected and corrected trends in a Figure similar to Wang et al. 2012. We use the following figure instead of Table 1 in the revised manuscript. The impacts of biases on calculated trends are also discussed in the text.

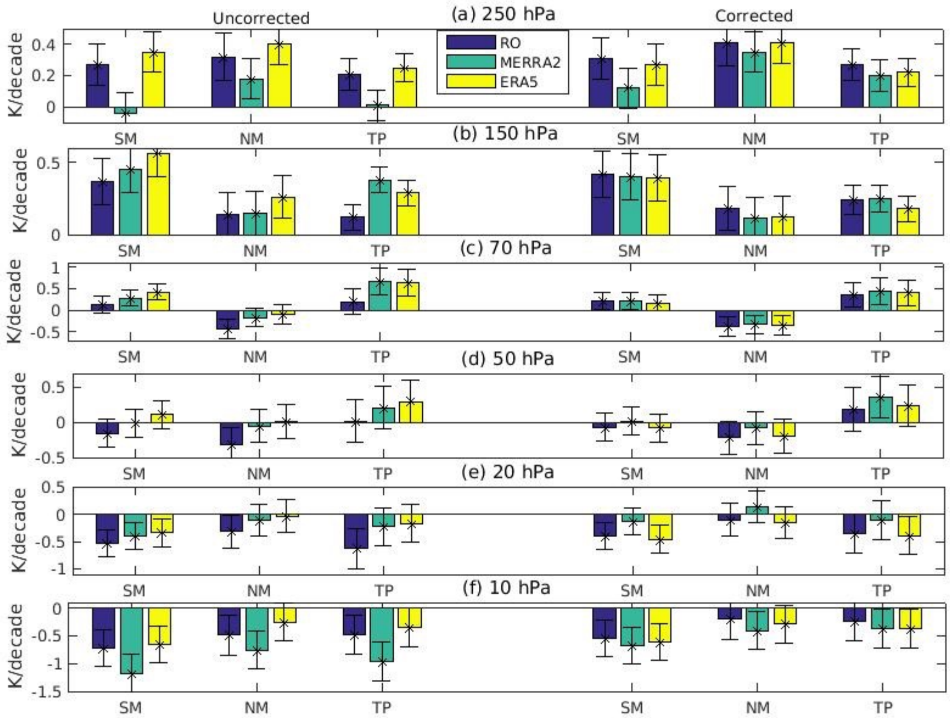

Figure 2: Estimated temperature trends in K/decade in different regions (SM: 25 °S-45 °S; NM: 25 °N-45 °N; TP: 10 °S-10 °N) from 2002 to 2017. (a-f) Trends in corrected and uncorrected data sets at 250, 150, 70, 50, 20 and 10 hPa. Error bars represent 95% confidence intervals.

5. The residuals and the anomalies of the multivariate regression (Figures 6 and 7) have same exact temporal structure and nearly the same magnitude. Do you know why? Can you directly compare and contrast your results with those of Randel and Wu (2014) who completed a detailed analysis using this method? It is concerning that the residuals have a magnitude that is roughly

the same as the signal, suggesting the majority of the signal is unexplained (e.g. QBO and ENSO both have amplitudes of less than 0.05K at this height)

According to your suggestion, we have made a detailed analysis using the method in
Randel and Wu (2014). Fig.2 shows the vertical profile of GNSS RO temperature variance in the deep tropics. The magnitude of annual cycle, QBO and ENSO related temperature anomalies shown in Fig. 2 is comparable to Randel and Wu (2014, Fig. 7). The residual at 150 hPa is much larger than the ENSO and QBO term at the same level. This explains the residuals and the anomalies of the multivariate regression have same temporal structure and nearly the same magnitude. At 70 hPa the QBO50 term is much larger than ENSO and QBO30 terms but still less than the residuals.

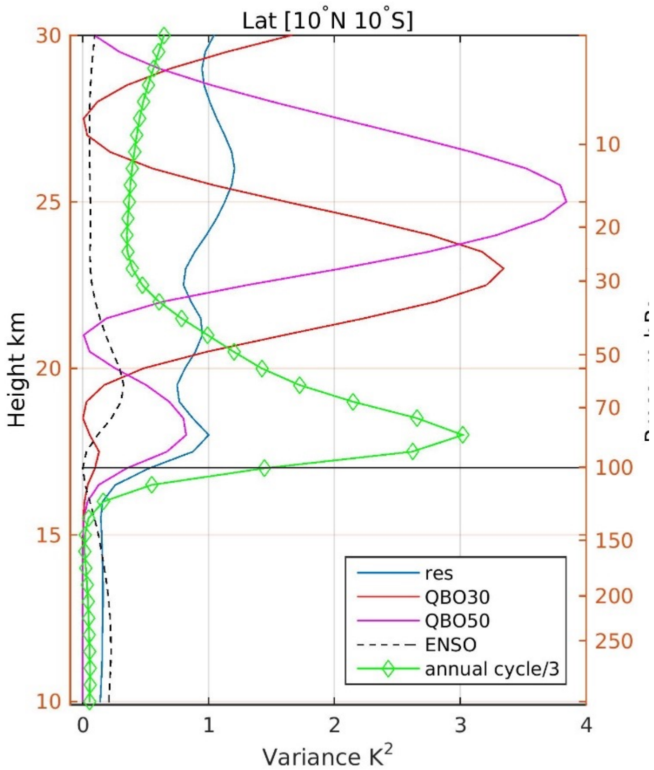

Figure 3: Vertical profile of GNSS RO temperature variance in the deep tropics (10°S-10°N) associated with annual cycle, QBO, ENSO, and residual variability. The variance for the annual cycle has been divided by three to fit within this scale. The horizontal line denotes the altitude of the time average lapse rate tropopause.

6. Another concern I have with this study is that the connections between ozone and temperature are very loosely made, and there are no analyses to support them. Calculations (such as changes in temperature structure through changes in ozone through either a climate model or radiative transfer model) have not been made, and not even a simple correlation analysis was performed. Many previous studies (e.g. Abalos et al. 2012, Maycock 2016, Gilford et al. 2016, to name just a few) have done detailed modeling, radiative calculations or statistical analyses, quantifying the

relationship between temperature and ozone. Instead, this paper simply notes "In the stratosphere, ozone distribution is highly correlated with the temperature change" (pg. 14, line 3) without actually showing any such correlations, and discusses some loose connections between temperature and ozone in section 3.4. Furthermore, it claims we need to "await further investigation" (pg. 3, line 27), but extensive research on this topic has been done! There is very little acknowledgement of the vast literature which has discussed this topic in detail, and the results herein are not framed within that context. Its important to perform some analysis to show how this work is valuable and contributing to our knowledge of ozone/temperature links (especially in the context of how this relationship changes between reanalyses and GPS).

We apologize for didn't clearly introduce results about the connection between ozone and temperature in previous studies. A correlation analysis was performed between temperature anomalies and ozone anomalies from 2005 to 2017 and the potential contribution of ozone changes to temperature trends was also estimated. Fig.3 show the correlation coefficient between ozone and temperature and the ozone contributions to temperature trends. In general, all strong positive correlation (>0.6) between ozone and temperature can be found from 100 to 20 hPa. The correlation coefficients of ozone/T are highest in tropics (~0.9). The correlation coefficient between SWOOSH ozone and GNSS RO temperature is highest in average. MERRA2 shows a similar correlation between ozone and temperature while the correlation in ERA5 is slightly weaker. While ozone and temperature are positively correlated, a decrease of ozone contributes to a cooling in the NH and in the tropical upper troposphere and mid stratosphere. Increases of ozone lead to a warming effect in the SH and the lower stratosphere in the tropics.

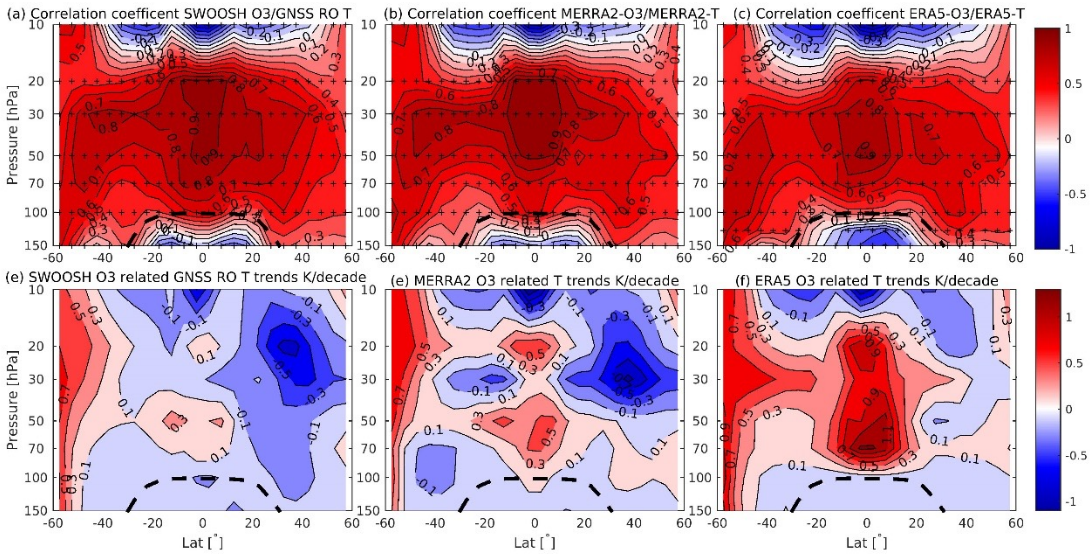

Figure 4: The correlation coefficients between SWOOSH ozone and GNSS RO temperature (a), MERRA2 ozone/T (b) and ERA5 ozone/T (c), which are calculated
from monthly deseasonalized anomaly time series from 2005 to 2017. The '+'

marked the significant values using a p-value 0.05 for testing the hypothesis of
no correlation. (d) SWOOSH ozone regressed GNSS RO temperature trends in K/decade; (e) MERRA2 ozone regressed temperature trends in K/decade; (f) ERA5 ozone regressed temperature trends in K/decade.

7. My primary concern with this paper is that it does not successfully and clearly
distinguishing itself as novel. The trend calculations (for instance for ozone, pg. 3, line 21) have been updated through 2016 in previous studies, so this paper represents a2-year improvement (and as noted above, the depth ozone research herein is not at a level commensurate with previous studies). Studies of UTLS temperature variability from GPS measurements have been very robustly presented in previous works (e.g. Abalos et al. 2012, Randel and Wu 2014). The use of the model to explore these processes is not well explained in the text, or compared with recently published studies which have done this (e.g. Randel et al. 2017).

To address this, I recommend the authors realign their motivation, highlighting that they are primarily concerned with comparing reanalyses and GPS in the UTLS with ERA5, in accordance with the S-RIP. Improvements in the ozone analyses and trend bias estimations in the context of comparing reanalyses will further improve on this narrative. Furthermore, the model should be brought introduced earlier in the paper as part of the motivation. This study can and will be valuable, but you need the tell and show the readers in clear language!

Thank you very much for the constructive comments. We agree to the reviewer that the motivation and the novel findings of this manuscript was not clearly addressed. We have rewritten the Introduction to highlight that our primary concern is to compare reanalysis data (in particular the ERA5 data) with the GPS-RO as the reviewer suggested. Other potential improvements of this manuscript than previous studies, i.e. an update of the temperature trend in the UTLS, the relationship between ozone and temperature changes and the attribution by model simulations, are also reorganized and addressed clearly in the revised manuscript.

Figure Comments:

All Figures: Please include units in all of your figure captions and titles/axes (where
relevant).
Thank you for your remarks. We have added units in all figures.
Figure 1: One of the ranges in the caption should be “SM” instead of “NM”. Also, it is not explained anywhere what is meant by SM and NM. Please add an explanation in
the text of the manuscript.
Sorry for missing the information. The SM and NM indicate Southern hemisphere Mid-latitude and Northern hemisphere Mid-latitude,

respectively. We have corrected the caption and added explanations in the revised manuscript.
Figures 4-5, 8-12, 14-15: Zonal mean figures would be improved if a line was added to indicate the climatological zonal mean tropopause height (using either the lapse rate tropopause or the cold-point tropopause, see Munchak and Pan 2014). These will likely vary from product to product and in the model, but it will help the read understand how your results vary with respect to the tropopause height.
Thank you for the suggestion. We have added the lapse rate tropopause in all figures.
Figures 1-3, 13: The x-axes on these timeseries plots are very hard to read because
the years are all squished together.
Yes, we have renewed figures.
Figures 11-12, 14-15 (and timeseries plots): Readers who are green-red will find it
very difficult to parse the green "+" markers or green lines in these figures. Please use some other way or color contrast this data which is color-blind friendly.
Sorry, we have changed the green "+" markers to black.
Table 1: This is a key result in the entire paper, yet its unclear. What are the +/- values in this table, are they the confidence intervals from your t-test? If so, please indicate so. It's also important that trends in the biases from GPS RO be included as a column at each level, for comparison.
The +/- values in this table are 95% confidence intervals for the coefficient estimates.
We have added the explanation in the text. The trends of the biases data are added in the table2.

Line-By-Line Comments:

Pg. 1, line 1: This first sentence is confusing as written.
We have rewritten this sentence.
Pg. 1, line 2 and elsewhere: Replace "were" with "are", and use present tense language throughout.
Thanks, we have checked carefully and updated the whole text.
Pg. 1, line 3+15: The first few sentences need to motivate the reader as to why your
study is a valuable contribution and novel. I recommend mentioning the model here in addition to later, and be specific about what model you are using and in what mode.
Thank you for the kind suggestion. We have rewritten the sentences as suggested.
Pg. 1, line 13: replace "the change of" with "discontinuities in"
Corrected.
Pg. 1, line 16: The use of "could be" shows how the shallow the ozone and physically based analyses in this study are. Further analyses should allow you to be more definitive here.
Yes, we have changed it.

Pg. 2, line 1: It is not “the” key region, it is “a” key region. Coupling is also important at high latitudes (e.g. sudden stratospheric warmings).
Corrected.
Pg. 2, line 3: Do you mean that temperatures in the UTLS respond to climate change?
That they affect other things (like water vapor) so they indirectly affect climate change? Please rewrite for clarity.
Yes, we have rewritten the sentence.
Pg. 2, lines 7-9: This sentence is confusing and should be rewritten.
Corrected.
Pg. 2, line 9: “through” should be “between”
Corrected.
Pg. 2, line 11: The term “underlying mechanisms” is used 4 times in this text without
any clear explanation of what it means. Its use is vague and unspecific, please rewrite to clarify exactly what is meant when you say “underlying mechanisms”.
“Underlying mechanisms” mean any possible mechanism/process that may influence the UTLS temperature, such as dynamical processes associated with SST, radiative effects by GHGs and ozone. We have updated the description in the manuscript.
Pg. 2, line 11: You are talking about trends in this paragraph, but now you mention
variability (which could be construed as interannual variability). important to keep them distinct throughout the paper, because they could be changing in different ways.
Thank you for your suggestion and we have deleted the word.
Pg. 2, line 24: This is very poorly written sentence, please rewrite for clarity.
Corrected.
Pg. 2, line 27: “Plenty” is a slang term and not professional. Please look throughout
your manuscript and replace these slang terms with more specific ones (e.g. “On one
hand”, pg. 3, line 4; “Same as”, pg. 6, line 24; etc.). Here I suggest: “assimilate
ground-based, satellite-based, and other data sources to provide the current...”
Thank you for your suggestion and we have corrected them in the text.
Pg. 2, line 31: The use of “perform” here is not correct. “may exhibit” would work.
Other times in this paper “perform” is also not used correctly (e.g. pg. 13, line 24); please rewrite each of these.
Corrected.
Pg. 3, lines 1-2: This sentence is poorly written and distorts the communication of your goal.
We have rephrased this sentence.
Pg. 3, line 9: While ozone changes could be a helpful indicator as you claim, you’ve barely touched on how complicated this is. Schoeberl et al. (2008)

did a rather complete study of this, but others (e.g. Polvani and Solomon 2012) have shown that it has rich nuances. You skip over that richness in your literature review here. I think its worth noting the efforts those papers made, and how your work is different.
Thank you for your suggestion and we have added literatures in the manuscript and the sentences to explain our work.
Pg. 3, line 10: “various of” should be “various”
Corrected.
Pg. 3, line 17: Very confusing as written.
Corrected.
Pg. 3, line 19: 15 hPa is well above the UTLS region!
We have deleted the sentence.
Pg. 3, line 29: The sentence is confusing as written.
Corrected.
Pg. 3, line 34: This a very abrupt transition introducing the model. This needs to be
done more smoothly and with better motivation as to why we are using the model.
Yes, we have added one sentence before introducing the model.
Pg. 4, lines 3-10: Much of this paragraph is repetive with previous ones and can be
removed.
Done.
Pg. 4, line 10: What is meant by “dynamical processing with SST”?
It means atmospheric circulation changes associated with SST. We have updated this sentence in the revised manuscript.

We thank the reviewer for all the comments and suggestions on the Introduction. The Introduction has been rewritten completely with all of comments considered.
Pg. 4, line 17: Seven years is not one decade. This is also very confusing as written.
Yes, we have changed the sentences.
Pg. 4, line 22: Are these measurement errors? Or differences from some other instrument?
They are estimated uncertainty for climate monitoring using GNSS radio occultation data.
Pg. 4, line 34: Can you provide a magnitude estimate for this “low effect”?
References show that less than 0.2K and I have added it in the manuscript.
Pg. 5, line 14: Was this linear interpolation done on a pressure grid or a height grid?
The linear interpolation has been done with logarithm pressure.
Pg. 5, line 17: What is meant by comparable here?
It means “similar”.
Pg. 5, line 25: add “to” before “which”
Corrected.
Pg.5 line 27: There’s no transition between these paragraphs. Are you introducing a
new dataset you will also use?

Yes, we have added a sentence for transition as follows:
"For better study the ozone variability, an independent data sets namely C3S SAGE-II/CCI/OMPS ozone products version 3 with 10 ° latitude bands are used."
Pg. 6, line 2: On what basis can you call this "a time period suitable for trend evaluation"?
Sorry for the vague description. What we want to say here is that the C3S covers the year 2002 and 2017, which can be directly compared with SWOOSH data. We have corrected this sentence.
Pg. 6, line 7: introduce this as version 3 in the very first sentence of this paragraph
instead.
We have introduced the version of data in the first sentence.
Pg. 6, line 16: As written, this sentence is unreadable. I don't understand what it is trying to say.
We have rewritten this sentence as follows:
"The newest ERA5 reanalysis, which is released by ECMWF in 2018, is also used."
Pg. 6, line 20: The link doesn't work as written, and should be more carefully cited in the bibliography.
Corrected.
Pg. 7, line 10: Please rewrite this confusing sentence.
We have rewritten this sentence as follows:
"The differences between these two simulations help to estimate the contribution of SST changes to temperature and ozone trends."
Pg. 7, line 11: I recommend renaming this section "Trend Calculations"
Updated.
Pg. 7, line 15: "Phenomenons" should be "phenomena"
Corrected.
Pg. 7, line 20: You have "a4" twice, but no solar component in equation 1.
Corrected.
Pg. 7, line 25: Is this a one-sided or two-sided t-test? Also, is this significance level the p-value? Please clarify your method.
It is a two-sided t-test and the significance level is 95%. We have clarified it in the text.
Pg. 7, line 29: The 400hPa level is well below the tropopause, especially in the tropics.
Thank you for your remarks. We use the Figure of 250hPa instead of the 400hPa level in the revised manuscript.
Pg. 8 line 11: What do you mean by "more disturbed" here?
The annual cycle at 100 hPa has substantial variability, which is not as regular as the annual cycle in the troposphere.
Pg. 9, line 22: why does the shortness of the period change this result? The shorter
period means that interannual variability should have more influence on the trend calculations.
Yes, we have added the sentences in the text.
Pg. 9, line 27: "getting less" should be "smaller"
Corrected.

Pg. 9, line 29: The sentence is very confusing as written.
This sentence has been rewritten as follows:
“By such a multiple linear regression, the influences of ENSO and QBO as well as the linear trend can be separated.”
Pg. 10, lines 4 and 12: What phase of ENSO or QBO? Please clarify throughout your
paper what phase you mean each time you discuss results for QBO and ENSO.
Positive phase ENSO and westerly QBO. We have clarified the phase in the paper.
Pg. 10, line 17: This title isn’t worded correctly. I suggest “Temperature Trends”
Corrected.
Pg. 10, line 28: I don’t know what you mean by this sentence, you might be missing a word?
Corrected.
Pg. 10, line 31: “MEERA2” should be “MERRA2”.
Corrected.
Pg. 11, line 5: Which tropopause? The cold point? The tropopause is a transition layer in the tropics (Fueglistaler et al. 2009)
The lapse rate tropopause.
Pg. 11, line 17: what dynamic process do you mean? Do you mean the influences of
SSTs on circulation? If so, please say so.
Yes, we have changed it.
Pg. 11, line 28: “so many” should be “as many”
Corrected.
Pg. 12, line 35: This is a nice physical discussion which is mired by very unclear
writing.
We have rewritten the discussion.
Pg. 13, line 1: Can you cite this? Many papers have shown this result.
Yes, we have cited previous studies.
Pg. 13, line 3: “That is not the truth” is not professional; please rewrite.
Yes, we have rewritten it.
Pg. 13, line 5: There is no observational evidence for ozone recovery yet, outside the
spring SH stratosphere (Randel et al. 2017).
We have rewritten the sentence.
Pg. 13, line 16: You haven’t done any attribution work, so this claim should be removed.
Corrected.
Pg. 13, line 22-24: These lines are very confusing; I don’t understand what you mean.
We have updated the sentence as follows:
“ERA5 shows obvious improvements of temperature data compared with ERA-I and also a slight better agreement with GNSS RO measurements than MERRA2.”
Pg. 13, line 29: 15 years is not “nearly 2 decades”.

Corrected.
Pg. 14, line 1: This is a run-on sentence, and its very hard to parse what your point is here. Please rewrite.
This sentence has be updated as follows:
"Again, ERA5 shows improved quality compared with ERA-I and has the best agreement with the GNSS RO data in the three reanalyses."
Pg. 14, lines 3: You have not shown this result.
Yes, we have added the content.
Pg. 14, line 5: This result isn't true for all datasets in your study, and you haven't clarified what period these trends are considered over in this discussion.
We have clarified the period in the discussion.
Pg. 14, line 14: Your results do not show this link, please don't make false claims without evidence. In fact, it has been shown previously to not be the case (Randel et al. 2017).
We have deleted it.
Pg. 14, line 17: Poorly written.
Corrected.

References

Wargan, K., Orbe, C., Pawson, S., Ziemke, J. R., Oman, L. D., Olsen, M. A., Coy, L., Knowland, K. E: Recent decline in extratropical lower stratospheric ozone attributed to circulation changes. Geophysical Research Letters, 45, 5166–5176, https://doi.org/10.1029/2018GL077406, 2018
Wigley, T.: Appendix A: Statistical issues regarding trends, in: Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences, edited by: Karl, T. R., Hassol, S. J., Miller, C. D., and Murray, W. L., A Report by Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC, USA, UNT Digital Library, 129–139, 2006.

Kris Wargan
Short comments

Dear Authors
Please consider these two comments, one scientific and one regarding data citation.
This is an interesting paper and I hope you will find my remarks helpful.
Thank you very much for the very useful comments. We have updated the method and citation as suggested and hope the manuscript has been considerably improved.

1) I really appreciate your discussion of the negative impacts of step-changes in the ozone observing system on ozone trends in MERRA-2. Even a cursory look at Figure 13 reveals that the discontinuity associated with the transition from MLS v2.2 to v4.2 in June 2015 is nontrivial, as you correctly point out in Section 3.4. I would like to draw your attention to the fact that it is possible and relatively simple to account for this, as well as the 2004 SBUV-to-MLS transition, precisely because these step-changes are so infrequent and well defined. In Wargan et al, 2018 (doi:10.1029/2018GL077406) we did it using an SD model simulation as a transfer function but it could also be done by

including a step-function proxy in the MLR. We tried the latter approach (not shown in our paper) and the result was very similar to that obtained using the transfer function approach. I suspect the MERRA-2 panel in Figure 14 would look different if a bias correction was applied. In fact, the analysis could be extended further back to 1998.
Thank you for your suggestion. We have corrected the discontinuity associated with the transition from MLS v2.2 to v4.2 in June 2015 with a step-function proxy in the MLR. The ozone trends have been updated in Figure 15 in the revised manuscript.

2) NASA GMAO asks the users of MERRA-2 data to explicitly cite the data collections used. Note that each MERRA-2 collection has a unique doi number listed in the file specs document https://gmao.gsfc.nasa.gov/pubs/docs/Bosilovich785.pdf For example monthly mean pressure-levels assimilated data ("M2IMNPASM" or *instM_3d_asm_Np*) could be cited as follows: Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 instM_3d_asm_Np: 3d,Monthly mean, Instantaneous, PressureLevel, Assimilation, Assimilated Meteorological Fields V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: [Data Access Date], 10.5067/2E096JV59PK7
Thank you for the information. We have added the citation in the revised manuscript.

Variability of temperature and ozone in the upper troposphere and lower stratosphere from multi-satellite observations and reanalysis data

Ming Shangguan[1], Wuke Wang[2,3,4], and Shuanggen Jin[5,6]

[1]School of Transportation,Southeast University, Nanjing 21189, China
[2]Institute for Climate and Global Change Research, School of Atmospheric Sciences, Nanjing University, Nanjing 210023, China
[3]Joint International Research Laboratory of Atmospheric and Earth System Sciences (JirLATEST), Nanjing University, Nanjing 210023, China
[4]Collaborative Innovation Center of Climate Change, Jiangsu Province, Nanjing 210023, China
[5]Shanghai Astronomical Observatory,Chinese Academy of Sciences, Shanghai 200030, China
[6]School of Remote Sensing and Geomatics Engineering, Najing University of Information Science and Technology, Nanjing 210044, China

Correspondence: Ming Shangguan(sgming@seu.edu.cn), Wuke Wang(wuke.wang@nju.edu.cn)

Abstract. Temperature and ozone changes in the upper troposphere and lower stratosphere (UTLS) are important components ~~and sensitive indicators~~ of climate change. In this paper, variability and trends of temperature and ozone in the UTLS ~~were~~ are investigated for the period 2002-2017 using the high quality, high vertical resolution ~~GPS RO data ,~~ GNSS RO data and improved merged satellite data sets~~(SWOOSH and C3S) and~~ . As part of the Stratosphere-troposphere Processes And their Role in Climate (SPARC) Reanalysis Intercomparison Project (S-RIP), three reanalysis data sets ~~(including the newest ERA5~~including the ERA-I, MERRA2 and ~~ERA-Interim) . All three reanalyses~~ the recently released ERA5 are evaluated for their representation of temperature and ozone in the UTLS. The recent temperature and ozone trends are updated by a multiple linear regression (MLR) method, and related to Sea Surface Temperature (SST) changes based on model simulations with NCAR's Whole Atmosphere Community Climate Model (WACCM).

All reanalysis temperatures show good agreement with the ~~GPS~~ GNSS RO measurements in ~~absolute values, annual cycleas well as interannual variabilities of temperature~~ both absolute values and annual cycle. Interannual variations of temperature related to QBO and ENSO processes are well represented by all reanalyses. However, ~~relatively large biases exist for the period 2002-2006, which reveals an evident discontinuity of temperature time series in reanalyses. Based on the multiple linear regression methods,~~ evident biases can be seen in reanalyses for the linear trends of temperature since they are affected by discontinuities in assimilated observations and methods. Such biases can be corrected and the estimated trends can be significantly improved. ERA5 is significantly improved compared with ERA-I and shows the best agreement with the GNSS RO temperature.

The MLR results indicate a significant warming of 0.2-0.3 K/decade ~~is found~~ in most areas of the troposphere with stronger increase of 0.4-0.5 K/decade in mid-latitudes of both hemispheres. In contrast, the stratospheric temperature decreases at a rate of 0.1-0.3 K/decade~~except that in the lower most stratosphere (~~, which is most significant in the Southern Hemisphere (SH).

Positive temperature trends of 0.1-0.3 K/decade are seen in the tropical lower stratosphere (100-50 hPa) in the tropics and parts of mid-latitude in the Northern Hemisphere (NH). ERA5 shows improved quality compared with ERA-Interim and performs the best agreement with the GPS RO data for the recent trends of temperature. Similar with temperature, reanalyses ozone are also affected by the change of assimilated observations and methods). Negative trends of ozone are found in NH at 150-100 Northern hemisphere (NH) at 150-50 hPa while positive trends are evident in the tropical lower stratosphere. Asymmetric trends of ozone can be found for both in the mid-latitudes of two hemispheres in the middle stratosphere, with significant ozone decrease in NH mid-latitudes and increase of ozone in the Southern Hemisphere (SH) mid-latitudes. According to model simulationsSH. Large biases exist in reanalyses and it is still challenging to do trend analysis based on reanalysis ozone data.

According to single-factor-controlling model simulations with WACCM, the temperature increase in the troposphere as well as ozone decrease in the NH stratosphere could be are mainly connected to the increase of Sea Surface Temperature (SST) SST and subsequent changes of atmospheric circulations. Both the increase of SSTs and the decrease of ozone in the NH contribute to the temperature decrease in the NH stratosphere. The increase of temperature in the lower stratospheric tropics may be related to an increase of ozone in that region, while SST increase contributes to a cooling in that area.

1 Introduction

The upper troposphere and lower stratosphere (UTLS) is the a key region for stratosphere-troposphere coupling and affects the content of trace gases in both the troposphere and the stratosphere (Staten and Reichler, 2008; Fueglistaler et al., 2014). Temperature change in the UTLS is an important component in of climate change and may act as a sensitive indicator of natural and anthropogenic climate forcing. A net warming in the troposphere and cooling in the stratosphere were reported over the past decades, which have been attributed to has been greatly concerned by numerous studies (Randel et al., 2009; Wang et al., 2012; Kim et al., 2 While measurements in the UTLS are relatively sparse, reanalysis data are widely used to investigate temperature variabilities (Xie et al., 2012; Wang et al., 2016). Atmospheric reanalysis data assimilate ground-based, satellite-based, and other data sources to provide the current best estimation of the real atmosphere with global spatial and temporal coverage. However, because of the radiative impacts of increasing greenhouse gases (GHG) and changes in ozone-depleting substances (ODS) (Randel et al., 2009; Flato et al. Recently, a slowing down of cooling in the lower stratosphere since 1998 (Polvani et al., 2017), or an increase of temperature in the TTL since 2001 (Wang et al., 2013) has been indicated, while the exact mechanism is still under debate (Wang et al., 2015; Polvani et al Disagreements through different observational data sets (Wang et al., 2012) and also between data and models (Kim et al., 2013) make it further complicated to fully understand the UTLS temperature variability and underlying mechanismslacking of high quality and high vertical resolution temperature observations and also the low vertical resolution of the model, the reanalysis data in the UTLS might be problematic (Zhao and Li, 2006; Trenberth and Smith, 2006, 2009). How accuracy the temperature field as well as its variability are represented in reanalysis data is required to be quantified.

Measuring the temperature in the UTLS has been problematic due to its strong variability around the tropopause. Ground-based A comprehensive assessment of the accuracy of the reanalysis temperature has been challenging because of the lacking of high quality observations with high temporal and high spacial resolution. For example, ground-based radiosonde measurements often have low temporal and spatial resolution (distributed in the northern hemisphere mostly)and also suffer from its inhomogeneity due to changes in instruments (Seidel and Randel, 2006; Wang et al., 2012). Nadir , while nadir sounding satellite measurements (e.g., Microwave Sounding Unit) can not well resolve the narrow vertical-scale features in the UTLS, which are essentially important for understanding processes related to the UTLS. Global Positioning System radio occultation (GPS . Global Navigation Satellite System Radio Occultation (GNSS RO) is a relatively new technology which measures the time delay in occulted signals from one satellite to another and provides information to derive profiles of atmospheric temperature and moisture. Since the Challenging Minisatellite Payload (CHAMP) mission launched in 2001, GPS GNSS RO has provided high quality and high vertical resolution temperature measurements in the UTLS for almost two decades. Due to its self-calibrating and not susceptible to instrument drift (Anthes et al., 2008), the GPS RO data GNSS RO provides a stable temperature record which is well suited for long-term trend studies. Several studies have been done for detecting possible temperature trends using about 10 years of RO data in the UTLS (Ladstädter et al., 2011; Steiner et al., 2011; Wang et al., 2015; Kishore et al., 2016). A cooling (~0.88) is observed at 30-10 and a warming trend (~0.82) is seen at 300 based on the COSMIC data from July 2006 to December 2013 (Kishore et al., 2016). Due to a short time period most of trends are not significant. One to validate the reanalysis data.

Atmospheric reanalysis has been developed for decades. While more and more observations are available and more advanced techniques are used in the assimilation system, new generation of reanalysis is expected to be significantly improved. The European Center for Medium-Range Weather Forecasts (ECMWF) released its fifth generation reanalysis (ERA5) in 2017. It is very interesting to see how the quality of temperatures in the UTLS has been improved in ERA5. The primary goal of this study is using the longer GPS RO record to update the recent variability of the temperature from 2002 to 2017 in the UTLS and analyze the underlying mechanisms.

Atmospheric reanalysis data, with plenty of observed data sources assimilated, are the current best estimation of the real atmosphere and provide excellent global spatial and temporal coverage of temperature. However, because of the lacking of high-quality and high-vertical-resolution temperature observations and also the low vertical resolution of evaluate the UTLS temperature in the model, newest ERA5 reanalysis using the GNSS RO as a reference. Within the context of the SPARC S-RIP, the Modern-Era Retrospective analysis for Research and Application, Version 2 (MERRA2) and the reanalysis data ERA-Interim (ERA-I) are also included for a comparison.

To give a comprehensive assessment of the reanalysis temperature in the UTLS, the interannual variations as well as the long-term trend of temperature are compared between the GNSS RO and different reanalysis data sets. Interannual variabilities of temperatures in the UTLS are related to complex processes, such as the Quasi-Biennial Oscillation (QBO) and the El-Niño Southern Oscillation (ENSO) (Xie et al., 2012; Randel and Wu, 2015; Garfinkel et al., 2018). QBO and ENSO related temperature signals in the UTLS might be problematic (Zhao and Li, 2006; Trenberth and Smith, 2006, 2009). In addition, while are analyzed to evaluate the capability of reanalysis data to well represent QBO and ENSO related signals. While assimilating many types of observations, reanalysis data suffer from instrument exchanges and perform may exhibit sudden changes as new data are assimilated (Sturaro, 2003; Sterl, 2004). The Such discontinuities may strongly influence the long-term trend calculated from reanalysis data. How well could the reanalysis data represent the interannual variability as well as long-term trend of temperatures in the UTLS is the second goal of this studyis to validate the most recent reanalyses, including the fifth generation European Center for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis (ERA5), the Modern-Era Retrospective analysis for Research and Application, Version 2 (MERRA2) and the ERA-Interim (ERA-I), and assessment their performance . .

Long-term trend is a key issue regarding to the UTLS researches. A net cooling in the stratosphere was seen over the past decades (Randel et al., 2009; Flato et al., 2014). However, large discrepancies of the temperature trends in the UTLS region.

Ozone, which is fundamental to stratospheric and tropospheric chemistry as well as radiative budget of global climate, is closely coupled to temperature changes in the UTLS. On one hand, changes in ozone concentrations impact temperature directly through its radiative effects (Forster et al., 2007) or indirectly through its modulation to atmospheric circulations (Polvani et al., 2017). On the other hand, most of ozone related chemical reactions are temperature dependenthave been reported between different observational/reanalysis data sets (Wang et al., 2012; Xie et al., 2012) and also between data and models (Kim et al., 2013). Recently, a slowing down of cooling in the lower stratosphere since 1998 (Polvani et al., 2017), or an increase of temperature in the tropical tropopause layer since 2001 (Wang et al., 2013) has been reported, which makes it more complicated to fully understand the UTLS temperature trend. Temperature changes could modify the production and loss rates and therefore impact ozone concentrations. In addition, they could both get affected by changes in atmospheric circulations. Analyzing ozone variability is then expected to be helpful for understanding processes that influences temperature changes in the UTLS are related to both internal processes, e.g. SST variations, and external forcing, such as greenhouse gases (GHG) and ozone-depleting substances (ODS) (Randel et al., 2009; Flato et al., 2014). If the slowing down or changing in sign of temperature in the UTLS persists in future is an open question. Whether the turning of temperature trends around 2000 is related to internal processes like SST variations (Wang et al., 2015, 2016), or caused by ozone changes (Polvani and Solomon, 2012; Polvani et al., still not clear. The third goal of this study is to update the recent temperature trend in the UTLS using a combination of GNSS RO and reanalysis data sets and attribute it to different factors like SST and ozone changes.

Ozone amount To understand the relationship between ozone and temperature changes in the UTLSare mainly measured by various of satellite missions. To date, the longest instrument records are Stratospheric Aerosol and Gas Experiment (SAGE)-II, which provided ozone data from 1984 to 2005 (Damadeo et al., 2013; Tummon et al., 2015). Since Aug. 2004 the Aura MLS ozone data provide continues ozone data (Waters et al., 2006). Over the past decade, there are also many new satellite-based instruments (ENVISAT, MIPAS, GOMOS, etc.) have made ozoneprofiles measurements but few continues data sets (Hassler et al., 2014; Te Therefore, several institutes and projects (National Aeronautics and Space Administration (NASA), Copernicus Climate Change Service (C3S), the Stratosphere- troposphere Processes And their Role in Climate (SPARC), etc.) developed long-term vertically resolved ozonedata sets for updated knowledge of long-term changes in the vertical distribution of ozone . .

It is obvious that there are many different results for recent ozone variability , the recent variability of ozone is also analyzed. Ozone is closely coupled to temperature changes in the UTLS. Abalos et al. (2012) studied the temporal variability of the upwelling near the tropopause using MLS (Microwave Limb Sounder) ozone/CO and ERA-I temperature/wind and demonstrated the high correlations between the upwelling, temperatures and tracers. Schoeberl et al. (2008) found that photochemical processes force fluctuations in the trace gases (such as ozone) to be synchronized with annual and QBO variations in the zonal mean residual vertical velocity. Changes in ozone concentrations may impact temperature directly through its radiative effects (Forster et al., 2007; Abalos et al., 2012; Maycock, 2016; Gilford et al., 2016) or indirectly through its modulation to atmospheric circulations (Polvani et al., 2017). The recent variability of ozone in the UTLS regions represented by different has been investigated by several studies. Harris et al. (2015) found some negative trend in the tropics around 15 and positive trends in the lower stratosphere at mid-latitudes and deep tropics based on the merged satellite ozone data from 1998 to 2012. Steinbrecht et al. (2017) updated the ozone profile trends for the period 2000 to 2016 and found a decreasing ozone in the tropics and at northern mid-latitude between 100 and 50 hPa. Ball et al. (2018) also indicated a continuous decline in the lower stratosphere (147-30 hPa at mid-latitudes or 100-32 hPa at tropical latitudes) from multiple satellite ozone data between 1998 and 2016. Chipperfield et al. (2018) extended the analysis to 2017 and argued that the ozone decline in the lower stratosphere is insignificant. They further concluded that the observed variations of ozone in the LS are mainly caused by atmospheric dynamics using a 3-D chemical transport model. Therefore, whether the ozone is increase or decline Whether the ozone is increasing or declining recently is still under debate, while its relationship to temperature changes trends awaits further investigations. Another goal of this study is to analyze

This study revisits the recent variability of ozone in the UTLS using different merged satellite by a combination of the SWOOSH (Stratospheric Water and OzOne Satellite Homogenized) and the C3S (Copernicus Climate Change Service) merged satellite ozone data sets.

RecentlyAt the same time, ozone content is represented as prognostic variables provided in almost all current reanalysis due to its important impact on stratospheric temperature (Dee et al., 2011; Davis et al., 2017). Although might be still problematic (Davis et al., 2017), ozone data from (Dee et al., 2011; Davis et al., 2017; Wargan et al., 2017). A comprehensive assessment of ozone data in reanalysis has been used to detect and attribute trends in lower stratospheric ozone (Wargan et al., 2017). The made by a previous study (Davis et al., 2017). However, the newest ERA5 reanalysis was not included in their study. As part of the SPARC S-Rip, ozone records from different reanalyses (ERA5 and MERRA2) are also analyzed and compared to merged satellite data sets in this study. In addition, coupled

Coupled chemistry climate models are useful tools and have been widely used to attribute climate variability. A series of model simulations with NCAR's WACCM (Whole Atmosphere Community Climate Model), which are used in this study to fully understand the exact reason of the recent temperature variability in the UTLS. WACCM is one of the two available atmospheric components of the Community Earth System Model (CESM), is used in this study to understand underlying mechanisms that influence recent variability and has been used widely in previous studies to detect and attribute the variabilities of temperature and ozone in the UTLS .

(Wang et al., 2015; Randel et al., 2017). In this study, we investigate the seasonal-to-interannual variability and detect the recent trends of temperature in the UTLS (400-10) using the high-quality and high-vertical-resolution GPS RO data for the period 2002-2017. Recent reanalyses, especially the newest ERA5 reanalysis are also analyzed and compared to the GPS RO data. At the same time, the ozone variability in the same period from 250 to 10 are compared and analyzed with the combined recorded of satellite ozone data and reanalyses. In totally, the two RO missions (COSMIC and CHAMP), two ozone

~~merged data (The Stratospheric Water and OzOne Satellite Homogenized data set (SWOOSH) and C3S) and three reanalyses MERRA2, ERA-I and newest ERA5 are included in the study. The multiple linear regression is used to calculate the trends. The WACCM model simulations with time varying and climatological SSTs are included to check the possible influence of dynamical processing with SST for the temperature and ozone variability.~~ single factor controlling simulations are conducted to quantify the relative contribution of different climate forcing.

The paper is laid out as follows: In sect. 2 we provide an overview of the used observational data sets, reanalyses, model and method for trend calculation. ~~Sect~~In sect. 3 we compare and analyze the temperature and ozone in absolute mean, anomalies and trend in vertically, regionally and globally. In the final section, we conclude with a summary.

2 Data and Methods

2.1 ~~GPS~~ GNSS RO Temperature Data

The Challenging Minisatellite Payload (CHAMP) became operational and produce 150 occultation events globally per day in 2001 (Wickert et al., 2001). ~~Around~~ Nearly one decade CHAMP data are available from May 2001 to Oct. 2008. In 2006 the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC), which is a constellation of six satellites, ~~provides~~ providing more than 10 times the number of observations (1000-3000 occultations per day). According to previous studies (Foelsche et al., 2008; Ho et al., 2009) , the mean temperature differences between the collocated soundings COSMIC and CHAMP were within 0.1 K from 200 to 20 hPa. Many studies have demonstrated that ~~GPS~~ GNSS RO temperature data have good quality in the range of 8-30 km (Schmidt et al., 2005, 2010; Ho et al., 2012). Ho et al. (2009) found that results from ~~GPS~~ GNSS RO show a mean temperature deviation of 0.05 K with a standard deviation of 1 K in the range of 8-30 km. ~~GPS~~ GNSS RO data are high precision and can be used to assess the accuracy of other detection techniques such as to correct the temperature bias of radiosondes in the lower stratosphere (Ho et al., 2016). Many reanalyses have already assimilated ~~GPS~~ GNSS RO bending angles.

In our study, we make use of monthly mean temperature data at 400-10 hPa (approximately 6.5-30 km) for the trend analysis, with which the essential atmospheric variability ~~can be already captured by~~ has already been captured by a single satellite (Pirscher et al., 2007; Foelsche et al., 2008; Ladstädter et al., 2011). Note that the region of 400-10 hPa is out of the definition of UTLS, which is usually defined as the region ±5 km of the tropopause. Here we focus on a broader region from the upper troposphere (400 hPa) to the mid stratosphere (10 hPa) due to the availability of GNSS RO temperature. More than 100 observations per month per 5 latitude grid can be provided by single satellite CHAMP. Much improved spatial coverage (more than 10 times number of profiles) appear since late 2006 due to the start of COSMIC mission. The high latitudes regions with low coverage of observations can cause large sampling errors. In consideration of large uncertainties caused by sparse data coverage at high latitudes, we consider only ~~GPS~~ GNSS RO data in latitude bands 60°S to 60°N here. According to ~~the many~~ previous studies (Foelsche et al., 2008; Scherllin-Pirscher et al., 2011; Ladstädter et al., 2011) the sampling errors have low effect (<0.2 K) on the trend calculation in mid-latitudes and tropics. The moisture-corrected atmospheric temperature profile (wetPrf) products of CHAMP and COSMIC provided by the UCAR COSMIC Data Analysis and Archive Center (CDAAC) are utilized. WetPrf products using one-dimensional variational method (1DVAR) have up to 100 m vertical resolution from 0.1 to 40 km and use low resolution ECMWF ERA-I profiles as background for 1DVAR technique (Wee and Kuo, 2014)(Wee and Kuo, 2015). The RO data we use in this study are processed in reprocessed and post-processed categories, which can provide stable and accurate observations for climate studies. The CHAMP wetPf2 version is 2016.2430 and COSMIC wetPrf version is 2013.3520 and 2016.1120.

Monthly zonal means on standard pressure levels (400, 350, 300, 250, 225, 200, 175, 150, 125, 100, 70, 50, 30, 20, 10 hPa) were determined, whereas 5°N non-overlapping latitude bands centered at 57.5°S-57.5°N were used. Larger discrepancies were observed for pressure levels above 400 hPa (below 6.5 km altitudes) due to high level of moisture in the lower troposphere (Kuo et al., 2004; Kuleshov et al., 2016). Therefore we focus on the data from 400 to 10 hPa in this work. The determination of monthly zonal means were performed in four steps. Firstly, all data in a given latitude bin were averaged and standard deviation of GPS GNSS RO with 100 m interval height are calculated. Secondly, all data were re-read and data exceeding 3 times of the standard deviation from the first zonal mean were removed as outliers at 400 levels. Thirdly, GPS GNSS RO temperature profiles were interpolated to the standard pressure levels using piecewise linear interpolation with logarithm pressure and if there existed large gaps in the profiles, no interpolation is made. In the last step the interpolated profiles are averaged to monthly mean temperatures on 17 standard pressure levels and 24 latitude bins. Monthly means with data points less than 20 observations per latitude bin are excluded for the trend analysis. Because the earliest available CHAMP data is since May 2001, we chose a comparable decadal 16 years time period from 2002 to 2017 for the temperature trend calculations.

2.2 Merged satellite Ozone Data

SWOOSH data set is a merged monthly mean of stratospheric ozone measurements taken by a number of limb sounding and solar occultation satellites from 1984 to present, and includes data from the SAGE-II (v7)/III(v4), UARS HALOE (v19), UARS MLS (v5/6), and Aura MLS (v4.2) instruments (Davis et al., 2016). The measurements are homogenized by applying corrections that are calculated from data taken during time periods of instrument overlap. The merged product without interpolation based on a weighted mean of the available measurements is used in this study on the pressure levels (316, 261, 215, 178, 147, 121, 100, 83, 68, 56, 46, 38, 32, 26, 22, 18, 15, 12, 10 hPa). SWOOSH uses SAGE-II as the reference for ozone data, to which other ozone measurements are adjusted. After Aug. 2004 the SWOOSH merged product is essentially the v4.2 Aura MLS data. The SWOOSH data used in this work is version 2.6 in 5° latitude zones monthly means.

For better study the ozone variability, an independent data sets namely C3S SAGE-II/CCI/OMPS ozone products are in version 3 with 10° latitude bands . are used. Compared with SWOOSH, The data merged 7 satellite instruments, including three instruments on board Envisate, Michelson Interferometer for Passive Atmospheric Sounding (MIPAS 2002-2012), Global Ozone Monitoring by Occultation of Stars (GOMOS 2002-2011), SCanning Imaging Spectrometer for Atmospheric CHartographY (SCIAMACHY 2002-2012), as well as Optical Spectrograph and InfraRed Imaging System (OSIRIS 2001-), SAGE-II(1984-2005), Ozone Mapping and Profiler Suite (OMPS 2012-) and Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS 2004-) (Sofieva et al., 2017). The absolute ozone values are adjusted to the mean of SAGE-II and OSIRIS ozone profiles in 2002-2005 (which nearly coincide also with GOMOS data). Ozone profile data are provided on an altitude grid and ancillary information is provided with the data products to allow conversion unit. The data records combine a large number of high quality limb and occultation sensors~~covering a time-period suitable for trend evaluation~~. The evaluation of ozone trends using the merged C3S data with other data sets has been ~~performed in~~ done by previous studies (Sofieva et al., 2017; Steinbrecht et al., 2017). The results show a good agreement between C3S and other data sets and the best quality of the merged data set is in the stratosphere in the latitude zone from 60° S to 60°N. The altitude levels (from 10 to 50 km in steps of 1 km) are interpolated to pressure levels using linear interpolation in log-presssure space. The monthly mean ozone molar concentration are converted to volume mixing ratio using the mean temperature provided by the C3S data. ~~The used C3S data in this work is version 3.~~

2.3 Reanalysis Data

ERA-I covers the period from 1979 until present, assimilating observational data from various satellites, buoys, radiosondes, commercial aircraft and others (Dee et al., 2011). ERA-I includes ~~GPS~~ GNSS RO bending angels from CHAMP, COSMIC, GRACE, MetOp, and TerraSAR-X and satellite vertical ~~ozones~~ ozone profiles from GOME/GOME-2, MIPAS, MLS, SBUV (Dee et al., 2011; Davis et al., 2017). Description of the ozone system and assessments of its ~~qulaity~~ quality have been provided by Dee et al. (2011); Dragani (2011). In this work, monthly means of ERA-I data (2.5°x2.5°) were averaged onto 5° latitude bins. ERA-I reanalysis is widely used for inter-comparisons and currently used as background information for wetPrf. For these reasons, we choose it for the comparison.

~~Besides ERA-I the currently newest ECMWF climate reanalyses~~ The newest ERA5 ~~with the same temporal and spatial resolution is also used. ERA5 is released~~ reanalysis, which is released by ECMWF in ~~2018 by ECMWF~~ 2018, is also used. Compared to ERA-I, ERA5 data assimilation system uses the new version of the integrated Forecasting System (IFS Cycle 41r2) instead of IFS Cycle 31r2 by ERA-I. In addition, various newly reprocessed data sets, recent instruments and cell-pressure correction SSU, improved bias correction for radiosondes etc, are renewed in ERA5. More information can be found in ERA5 data documentation https://confluence.ecmwf.int/display/CKB/ERA5+data+documentation#ERA5datadocumentation-Observations. Ozone and temperature monthly means at 17 standard pressure levels from 400 to 10 hPa are selected in this study.

MERRA2 is the latest atmospheric reanalysis of NASA's Global Modeling and Assimilation Office (GMAO) with data resolution 0.5°x0.625° (Gelaro et al., 2017). ~~Same as~~ For analysis we use monthly mean assimilated ozone and temperature data on pressure levels (Modeling and Office, 2015). In conformity with ERA-I, the MERRA2 data were averaged onto 5° latitude bins with weighted mean method. Compared with ERA-I/ERA5, MERRA2 starts to assimilate ~~GPS RO since~~ GNSS RO beginning in Jul. 2004 and MLS ozone data ~~since~~ beginning in Oct. 2004 (earlier SBUV observations) (McCarty et al., 2016). For ozone data MERRA2 assimilated MLS instead of SBUV since Oct. 2004 ~~(Gelaro et al., 2017).~~ (Gelaro et al., 2017). Monthly means of data at 15 standard pressure levels (400, 350, 300, 250, 200, 150, 100, 70, 50, 40, 30, 20, 10 hPa) are selected for the study. Wargan et al. (2017) provided a comprehensive description and validation of the ~~MERRA-2~~ MERRA2 ozone product.

2.4 Model simulations

The Whole Atmosphere Community Climate Model, version 4 (WACCM4) is used here in its atmosphere-only mode. The horizontal resolution of the WACCM4 runs presented here is $1.9° \times 2.5°$ (latitude $\times$ longitude). More details of this model are described in Marsh et al. (2013). WACCM4 uses the finite-volume dynamical core with 66 standard vertical levels (about $1\ \mathrm{km}$ vertical resolution in the UTLS). Here we use the special version with finer vertical resolution, WACCM_L103 (Gettelman and Birner, 2007), with 103 vertical levels and about $300\ \mathrm{m}$ vertical resolution in the UTLS. This high vertical resolution version has been proved ~~for a better representation to~~ to better represent the detailed thermal structure as well as interannual-to-decadal variations in the UTLS (Wang et al., 2013, 2015).

A hindcast simulation (hereafter termed as the Transient run) was done for the period 1995-2017 to reproduce the recent temperature and ozone variability in the UTLS. The model was forced by observed Greenhouse Gases (GHGs), ozone depleting substances (ODSs) and solar irradiances, nudged QBO (Quasi-Biennial Oscillation) (Matthes et al., 2010) and prescribed SSTs (using the HadISST data set (Rayner et al., 2003)). The first 7 years (1995-2001) are not analyzed for a spin-up. Based on this simulation, a FixSST run was integrated for the same period and using the same climate forcing except that SSTs were fixed to climatological values. The ~~difference~~ differences between these two simulations ~~indicate SST impacts on the atmosphere~~help to estimate the contribution of SST changes to temperature and ozone trends.

2.5 ~~Trends Methodology~~Trend Calculations

From the monthly zonal mean time series the seasonal cycle is firstly calculated, and monthly zonal anomalies are estimated by subtracting the seasonal cycle from each individual monthly mean. This data analysis ~~was~~ is performed for each data set and zonal bin. The calculated anomalies are the basis for trend calculations. The QBO and ENSO (El-Niño Southern Oscillation) are the most important ~~phenomenons~~ phenomena that affects interannual variability of the UTLS. To exclude the effects of QBO and ENSO, we apply a ~~simple~~ multiple linear regression (MLR) based on the temperature monthly anomalies (Eq. 1) (von Storch and Zwiers, 2002).

$$y(t) = a_0 + a_1 \cdot t + a_2 \cdot ENSO(t) + a_3 \cdot QBO50(t) + a_4 \cdot QBO30(t) \quad (1)$$

The regression coefficients comprise a constant a_0, the trend coefficient a_1, the ENSO coefficient a_2, the QBO ~~coefficient~~ coefficients a_3 and a_4~~and the solar cycle coefficient a_4~~. The QBO30 and QBO50 indexes for the period 2002-2017 are normalized to unit variance from the CDAS Reanalysis data, which are the zonally averaged winds at 30 and 50 hPa and taken from over the equator (http://www.cpc.ncep.noaa.gov/data/indices/). The ENSO MEI indexes are obtained from NOAA on the six main observed variable (sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature and total cloudiness fraction of the sky) over the tropical Pacific (http://www.cdc.noaa.gov/people/klaus.wolter/MEI/table.html). ~~The t-statistic~~ A two month time lag for the ENSO index is used following previous studies (Randel and Wu, 2015; Randel et al., 2017). The two-sided Student's t test is used to test for a significant linear regression relationship between the response variable and the predictor variables. The significance level is set to be ~~0.05~~95%.

3 Results and Analysis

3.1 Time series of temperature

Figure 1 shows the initial time series of zonal mean temperature at ~~400~~ 250 hPa from the ~~GPS~~ GNSS RO observations and different reanalyses (ERA5, MERRA2 and ERA-I) as well as ~~the relative~~ their differences between reanalyses and the ~~GPS~~ GNSS RO data. Three latitude bands are selected to indicate temperature variations in the tropics (TP, 10°S-10°N), ~~mid-latitude~~ mid-latitudes in the NH (NM, 25°N-45°N) and ~~SH (~~mid-latitudes in the SH (SM, 25°S-45°S). Seasonal variations are relatively small in the tropics while evident annual cycle can be seen in mid-latitudes of both hemispheres. Generally, reanalyses show good agreement with the ~~GPS~~ GNSS RO in monthly absolute values as well as seasonal variations except that MERRA2 shows obviously positive bias compared with other data sets in the TP. Seen from the differences between reanalyses and the ~~GPS~~ GNSS RO, the bias of ERA5 and ERA-I are less than ~~0.3~~ 0.5 K except in mid-latitude for the period 2002-2006, which shows bias up to ~~0.6 K~~1 K. As the 5th generation of the ECMWF reanalysis, ERA5 shows slightly better agreement than ERA-I in the tropics. Temperature in ERA-I is obviously warmer than the ~~GPS~~ GNSS RO of about 0.1-0.2 ~~K~~K, while ERA5 temperature shows differences of less than 0.1 K compared with the ~~GPS~~ GNSS RO data. Warm ~~bias of 0.3~~ biases (0.2 K ~~is~~ in NM/SM and 0.7 K in TP) are seen for MERRA2 in all selected regions, which is over ~~0.9~~ 1 K ~~in mid-latitude~~ for the period 2002-2006.

At 100 hPa, as indicated by Figure 2, more evident seasonal variations of temperature can be seen in the tropics, with similar amplitude to that in mid-latitudes of both hemispheres. ~~It is note worthy that the annual cycle of temperature at 100 in mid-latitudes are more disturbed than at 400 in the upper troposphere.~~ Compared with the ~~GPS~~ GNSS RO temperature, ERA-I shows evident cold bias in the tropics during the period 2002-2006. For ERA5, such bias is largely corrected. For the later period 2007-2017, the differences between three reanalyses and the ~~GPS~~ GNSS RO are comparable in magnitude, although the ERA5 shows slightly better agreement with ~~GPS~~ GNSS RO measurements. In mid-latitudes of both hemispheres, very similar characteristics can be seen through the three reanalyses, which show slightly better agreement with the ~~GPS~~ GNSS RO than in the tropics. However, relatively large bias can still be seen in the early stage from 2002 to 2006.

Temperature in the lower stratosphere (70 hPa) shows clear annual cycle in the tropics (figure 3(a)). However, the annual minimum and maximum values vary year-to-year, which indicate influences from the QBO. Large sub-seasonal fluctuations of temperature can be seen in mid-latitude of the NH, which is obviously different from that in the SH. That is related to strong equatorial as well as extra-tropical wave activities in this region. Again, large differences up to 1 K exists between the reanalyses and the ~~GPS~~ GNSS RO observations during the first stage 2002-2006. ERA5 shows obvious cold bias in all selected regions while MERRA2 is anomalously warmer than the ~~GPS~~ GNSS RO in mid-latitudes of both hemispheres. ERA-I, however, has no consistent warm or cold bias and shows the best agreement with the ~~GPS~~ GNSS RO for the period 2002-2006. For the latter stage of 2007-2017, ERA5 shows the best agreement with observations (differences within 0.2 K) while the other two reanalyses are slightly (about 0.2 K) warm biased.

Note that the bias is particularly large during ~~2001-2006~~ 2002-2006 for all reanalyses. This should be related to the assimilation of large number of COSMIC data since late 2006, which may cause sudden changes in reanalyses (Sturaro, 2003; Sterl, 2004). At the same time, the ~~GPS~~ GNSS RO data could be also affected by the transition from the single CHAMP satellite to six COSMIC satellites since late 2006. To quantify the sampling errors and bias between two RO missions, we compared COSMIC and CHAMP monthly means for their overlap period of Jun. 2006-Sep. 2008. In addition, the lapse rate tropopause is calculated using the GNSS RO data with the method described in Fueglistaler et al. (2009) and shown in figure 4(a). Figure 4(b) shows that COSMIC monthly zonal mean temperatures are consistent colder (0.1-0.2 K) than CHAMP in the stratosphere. ~~This~~ The cold is consistent with previous studies (Foelsche et al., 2008; Ho et al., 2009), although the differences between CHAMP and COSMIC are slightly larger than 0.1 K in some areas in the middle stratosphere (50-10 hPa). According to Schrøder et al. (2007); Leroy et al. (2018) the cold bias between CHAMP and COSMIC is the consequence of a change in the signal-to-noise ratio from 550 in CHAMP to 700 in COSMIC. In addition, the ribbed pattern in the meridional structure of the bias in the figure 4 is a consequence of sampling error (Leroy et al., 2018). The bias between COSMIC and CHAMP was computed from the 28-month period of overlap and removed from CHAMP-retrieved temperature for the further analysis in this work.

Figure 5 shows differences between three reanalyses and the corrected CHAMP for the period 2002-2006 and COSMIC for the period 2007-2017, respectively. For the first stage, MERRA2 shows warm bias of 0.1~~-0.3~~ -0.2 K in the upper troposphere, cold bias of 0.1~~-0.4~~ -0.3 K in the lower stratosphere and warm bias of 0.1-0.5 K in the ~~tropical~~ middle stratosphere. ERA5 shows relatively small cold bias of 0.1-0.2 K for almost the whole UTLS region. ERA-I shows warm bias of 0.1~~-0.5~~ -0.3 K ~~around the tropical tropopause~~ in the upper troposphere and cold bias of 0.1~~-0.5~~ -0.4 K in the middle stratosphere in both tropics and SH. For the second stage, differences between all three reanalysis and the ~~GPS~~ GNSS RO are much smaller. That is because the reanalyses are better constrained by large number of COSMIC measurements. MERRA2 shows ~~cold bias of about~~ differences with GNSS RO less than 0.1 K ~~in the upper troposphere, warm bias of 0.1 in the lower stratosphere and~~ except that cold bias of ~~0.1~~ about 0.2 K ~~in the middle stratosphere~~at 10 hPa and northern mid-latitudes at 200-250 hPa. ERA5 shows perfect agreement to the COSMIC with differences less than 0.1 K in most of the UTLS region except that in northern mid-latitudes (100-50 hPa) with warm bias 0.1 K. Bias in ERA-I is also quite small with warm bias of about 0.1 K only in the tropics around the tropopause and southern mid-latitudes near 10 hPa.

In summary, reanalyses show very good agreement with the ~~GPS~~ GNSS RO measurements in sub-seasonal to seasonal variations of temperature in the UTLS region. For the climatological values, a notable change around late 2006 can be found in all reanalyses. Relatively large bias of 0.1-0.5 K can be seen in MERRA2 and ERA-I for the first stage 2002-2006 while very good agreement can be seen between all reanalyses and the ~~GPS~~ GNSS RO measurements for the 2007-2017. As the newest reanalysis, ERA5 shows relatively small bias of 0.1-0.3 K during 2002-2006 and ~~performs~~ has the best agreement with ~~GPS~~ GNSS RO in general. To eliminate the effect of these discontinuities for further studies, reanalysis temperatures were corrected by using a transfer function approach similar to Wargan et al. (2018). The corrected GNSS RO temperature has no significant discontinuities and was used as a common baseline. Details of the bias correction for reanalysis temperatures are provided in the supplementary information (Figure S1).

3.2 Interannual Variability of temperature

Figure 6 shows one example of deseasonalized monthly anomalies of temperature in the tropical upper troposphere (10°S-10°N, at 150 hPa). As demonstrated in Figure 6a, temperature ~~performs~~ exhibits clear interannual variations, which is related to ENSO and QBO as indicated by previous studies ~~(?)~~(Randel and Wu, 2015). While the period of analysis is relatively short, such interannual fluctuations may significantly affect the calculation of linear trends. To estimate the influences of ENSO and QBO, a multiple linear regression method is applied as introduced in section 3.1. Figures 6d-f indicate contributions of QBO50, QBO30 and ENSO, respectively. ENSO contributes the largest and significant interannual variations of temperature in tropical upper troposphere with amplitude of about 0.5 K while QBO has only small and insignificant contributions. At lower levels in the free troposphere, the QBO contribution is ~~getting less~~ smaller and the impacts of ENSO are more significant. Reanalyses ~~perform~~ reveal a very good agreement with each other as well as the ~~GPS~~ GNSS RO in ENSO related contributions (Figure 6f) but show larger spread for QBO contributions. For the shorter period the interannual variability should have more influence on the trend calculations. By such a multiple linear regression, the influences of ENSO and QBO ~~are expected to be excluded and~~ as well as the linear trend ~~is therefore estimated~~can be separated. Seen from Figure 6c, ~~GPS~~ GNSS RO indicates an increase of 0.4 K in temperature for the whole period 2002-2017. ~~MEERA2 shows a stronger increase of 0.6 while the~~ The ERA-I ~~is almost flat.~~ trend is smallest (0.1 K/decade). According to Simmons et al. (2014), local degradation occurs near the sub-tropical tropopause whereas substantial amounts of warm-biased aircraft data are assimilated since 1999. After 2006, while large number of COSMIC data is assimilated, this warm bias disappeared. This anomalous warm temperature for the short period 1999-2005 leads less warming in this region by estimated ERA-I time series. Such bias has been corrected in ERA5 ~~, however, shows the best agreement with GPS ROwith an increase of about 0.5 K~~temperature data. ERA5 shows obviously better agreement with GNSS RO.

In the lower stratosphere, as illustrated in Figure 7, interannual variations of temperature are dominated by QBO, with amplitudes of over 1 K for QBO50. The ENSO effects are insignificant with an amplitude of about 0.5 ~~K. GPS~~ K. GNSS RO indicates an increase of ~~0.5~~ 0.55 K as seen in Figure 7c. MERRA2 and ERA-I/ERA5 show similar increase of ~~1~~ 0.65-0.7 K which is stronger than ~~GPS~~ GNSS RO. The relative contributions of ENSO and QBO to interannual variations of zonal mean temperatures in the UTLS are shown in Figures 8-10.

Consistent with previous studies ~~(?),~~ (Randel and Wu, 2015), positive ENSO is associated with warm temperature anomalies of 0.1-0.4 K in tropical upper troposphere and cold temperature anomalies of 0.1~~-0.4~~ -0.5 K above the tropopause in the tropics (Figure 8). ~~Contrast~~ In contrast to the tropics, anomalous cold temperatures can be seen in the sub-tropics below 100 hPa while warm temperature anomalies exist above 100 hPa. All three reanalyses show consistent pattern as seen in ~~GPS~~ GNSS RO associated with ~~ENSO. However, ENSO signals in tropical upper troposphere are slightly stronger in MERRA2 compared with GPS RO and other reanalyses, while ERA5 shows relative weak signals in subtropics above 100 .~~ positive ENSO.

As a stratospheric phenomenon, westerly QBO affects the temperature mainly in the upper atmosphere above 100 hPa. The spatial structure of temperature anomalies associated with ~~terms~~ wind terms in m/s of QBO50 and QBO30 are shown in Figures 9-10. QBO50 is associated with warming in the lower most stratosphere (100-50 hPa) and cooling in middle stratosphere (50-

15 hPa) in the tropics. Sub-tropics and mid-latitudes, however, show out-of-phase variations with significant warming signals. QBO30 contributes to similar temperature variations except that the signals are spatially orthogonal with the patterns associated with QBO50 (Figure 10). Reanalyses show very good agreement with ~~GPS~~ GNSS RO in both spatial pattern and magnitude for QBO related temperature variations as illustrated in Figures 9-10.

3.3 ~~Linear trend of temperature~~Temperature trends

Figure 11 summarize the spacial distribution of temperature trends based on ~~GPS~~ corrected GNSS RO and reanalyses for the time period 2002-2017. From the ~~GPS~~ GNSS RO measurements, positive trends of 0.2-0.3 K/decade are significant in most areas of the troposphere with stronger warming up to 0.4-0.5 K/decade in mid-latitudes of both hemispheres. At the same time, negative trends of 0.1-0.3 K/decade are evident in the stratosphere ~~except that in~~ (50-10 hPa). In the lower most stratosphere (100-50 hPa), positive temperature trends are significant in the tropics~~and parts of mid-latitude in the NH, whereas the temperature trends are positive.~~. This is consistent with previous studies (Wang et al., 2013, 2015; Polvani et al., 2017), which indicated a warming in this region since 2001. However, the trends shown here (0.3 K/decade in maximum) are much smaller than that in their results (e.g., up to 1.6 K/decade in Wang et al. (2013)). Seen from the time series of temperature at 70 hPa (Figure 7), the temperature increases from 2002 until 2011 and then declines (or stop to increase) after that.

Reanalysis data show good agreement with the ~~GPS~~ GNSS RO for the general pattern of temperature trends. However, ~~neutral~~ slightly smaller trends are found in MERRA2 in the tropical free troposphere (400-200 hPa), which could be related to the observed warm bias during 2002-2006 in MERRA2 as illustrated in Figure 5. ERA-I shows ~~insignificant negative trends around 225-175~~ neutral trends around 150-100 hPa in the tropics (~~20~~15°~~S-20~~S-15°N), which is ~~not observed~~ positive by other data sets~~. According to Simmons et al. (2014), local degradation occurs near the sub-tropical tropopause whereas substantial amounts of~~, which should be also related to the warm-biased aircraft data ~~are assimilated since 1999. After 2006, while large number of COSMIC data is assimilated, this warm bias disappeared. This anomalous warm temperature for the short period 1999-2005 leads less warming in this region as estemated by ERA-I. Such bias has been corrected in ERA5~~as mentioned in section 3.2. Very good agreement can be seen between ERA5 and the ~~GPS RO~~ GNSS RO data in the troposphere with very similar spacial pattern and comparable magnitude of warm in the troposphere.

In the stratosphere, the negative trends in ~~MEERA2 are too strong while that in~~ ERA-I are too weak and less significant in the SH. At the same time, positive trends in NH are stronger in both ~~ERA5~~ MERRA2 and ERA-I than that in ~~GPS~~ GNSS RO. Again, ERA5 shows the best agreement with ~~GPS~~ GNSS RO measurements with consistent pattern and comparable magnitude~~except that the negative trends in mid-latitude (around 30°N) lower stratosphere (150-50) in ERA5 are weaker and less significant than that in GPS RO~~. At 10 hPa in the tropics, all the ~~all~~ data sets show negative trends except ERA-I. According to Simmons et al. (2014), the large differences between MERRA2 and ERA-I at 10 hPa are associated with differing treatments of the change from SSU to AMSU-A and the availability of increasing amounts of largely unadjusted radiosonde data. While cell-pressure correction to SSU has been done in ERA5, ~~ERA5 data show~~ it shows similar cooling trends to observations at 10 hPa. Also notable difference between ~~GPS~~ GNSS RO and reanalyses can be seen in the tropics (5°S-20°N) around the lapse rate tropopause. Neutral ~~or insignificant positive~~ trends are found by ~~GPS RO~~ GNSS RO and ERA-I in this region, while

ERA5 and ERA-I show significant shows insignificant positive trends (0.4 0.2 K/decade) . This is related to the cold bias of ERA5 in this region during 2002-2006. In addition, as and MERRA2 shows insignificant negative trends (-0.1 K/decade). As a transition zone between the troposphere and the stratosphere, opposite sign could appear in neighboring layers below or above the tropopause, which causes large uncertainties in estimated trends around the tropopause.

Figure 12 further illustrates the temperature trends based on uncorrected/corrected GNSS RO and reanalysis data sets in three regions (SM: 25°S-45°S; NM: 25°N-45°N; TP: 10°S-10°N) at selected pressure levels (250, 150, 70, 50, 20, 10 hPa). The temperature increase in the upper troposphere is stronger and the cooling in the stratosphere gets weaker after the correction of the GNSS RO data. The differences of temperature trends between reanalysis and GNSS RO measurements become much smaller after corrections. For example, MERRA2 shows significant warming at 250 hPa in the SM after the correction, which is more consistent with the GNSS RO data. The unrealistic strong cooling in MERRA2 at 10 hPa is significantly reduced by the correction. Overall, the ERA5 data show the reanalysis data represent the temperature trends well from the upper troposphere to the mid-stratosphere after the correction, although obvious differences can be seen between reanalysis and the GNSS RO measurements. As the newest reanalysis, ERA5 shows the best agreement with the GPS GNSS RO measurements among most of areas as demonstrated in this study, which could also be confirmed by table **??**. Table **??** shows .

Note that the temperature trends based on GPS RO and reanalysis data sets in three regions (SH, NH, TP) at selected pressure levels (250, 150, 70, 50, 20, 10). discussed above are based on a relatively short data record of 16 years. The statistically significance of the obtained trends must be specially concerned since the trend assessment from such a short period can be strongly influenced by start/end years (Bandoro et al., 2018; Santer et al., 2017). Beside the two-sided Student's t test as mentioned in section 2.5, a signal-to-noise study is also included. The background noise of 16-year temperature trends are estimated by three fully coupled CESM simulations, which were integrated 145 years (1955 to 2099) with anthropogenic emissions (GHGs and ODSs) fixed to values at 1960. We fit linear trends to overlapping 192-month segments of the 1740-month in each of CESM runs and then the noise can be calculated by the standard deviation of the 16-year trends. More details of the CESM simulations and the methods can be seen in the supplements. The signal to noise ratios of 16-year GNSS RO temperature trends are shown in Fig. S2. Seen from Fig. S2, the areas with significant trends are smaller than that shown in Figure 11 in the main text. However, there are still significant signals in the mid-latitudes of the upper troposphere, around the tropopause and in the SH in the middle stratosphere. All the significant regions in Figure S2 are actually the most important areas with strongest and significant trends in Figure 11. This suggests that the significant trends shown in Figure 11 are robust except that in the tropics whereas the standard deviation of the trends are the strongest.

To explain the underlying mechanisms such as dynamical processes associated with SST of the illustrated temperature trends, two WACCM simulations as described in section 2.4 were employed. Figure 13 shows the temperature trends from the Transient run and the FixSST run as well as their differences. The Transient run with varying SST (Figure 13a) shows comparable positive trends (0.2-0.3 K/decade) in the troposphere and negative trends (0.1-0.5 K/decade) in the stratosphere (see Figure 11 for a comparison). While the SSTs are fixed to climatological values, which means only radiative effects from GHGs and ODSs are included, the positive trends in the troposphere disappear or becomes become much weaker (Figure 13b). This reveals that dynamic processes the influences of SSTs on circulation are the main reason for the warming temperature trends in troposphere, which can be confirmed by the differences between these two runs (Figure 13c). The positive trends above the tropical tropopause (100-50) as well as negative temperature trends in the stratosphere (tropics and SH) persist in the FixSST run. This indicates that such changes in temperature are dominated by radiative effects associated with increases of , which illustrates other factors like radiative effects from GHGs and ozone recovery. The significant coolingtrends at 150-50 contribute to such cooling. For the temperature trends above the tropical tropopause (100-50 hPain the NH subtropics and insignificant trends above are connected with both radiative and dynamical effects), the weak warming is related to combined effects of SSTs (contribute to a cooling) and other effects (lead to a warming).

3.4 Coupling with ozone

As described in the Introduction, changes in temperature and ozone are closely coupled to each other. Analyzing ozone variations at the same time is therefore useful for attributing temperature trends in the UTLS. Figure 14 shows the initial ozone time series from the SWOOSH, C3S, MERRA2 and ERA5 as well as their differences using the SWOOSH data as a reference in three regions at 70 hPa. The ERA-I is not included here for ozone analysis because it does not assimilate so much as many ozone measurements as ERA5 and MERRA2. Although the phase and amplitude agree well in general, the absolute ozone values have large differences between different data sets. Obvious missing data and extreme values exist in both SWOOSH and C3S data sets during 2002-2004, while a discontinuity in the MERRA2 and ERA5 time sereis series occurs in mid-2004 when Aura MLS mission starts. As illustrated in Figure 14, extreme large values are observed by SWOOSH and C3S around 2003. The reason is the limited number of observation in this period, which could cause large sampling errors and uncertainties in ozone data. At the same time, since the reanalysis is less constrained during this period, large bias can be seen in both MERRA2 and ERA5 compared to observations (Figures 14b, d and f). After 2006, SWOOSH uses MLS ozone data only (Davis et al., 2016) and MERRA2 also uses MLS instead of SBUV ozone data since Oct. 2004 (Gelaro et al., 2017). Therefore the MERRA2 ozone data have good agreement with SWOOSH data. Another discontinuity in the MERRA2 and ERA5 time series occurs around 2015. According to McCarty et al. (2016), MERRA2 starts to use the version 4.2 MLS ozone data instead of version 2.2 since June 2015, which cause data discontinuities at 250-70 hPa. As seen in Figures 14b, d and f, ozone in MERRA2 is 50-150 ppbv lower than that in SWOOSH and C3S. ERA5 combined more satellite data (SBUV and MLS) than MERRA2, which leads to larger variability of ozone in ERA5 since the different data sets and different ways for merging the data have large influences on the ozone data. The missing data and extreme values in SWOOSH and C3S, as well as the data discontinuities in MERRA2 and ERA5 around years 2004 and 2015 can also be seen at other pressure levels (See Figures S1-S2 S3-S4 for details).

To examine the connection between the vertical temperature changes and ozone distribution, ozone trends are analyzed in the stratosphere from 250 to 10 hPa. In consideration of poor ozone dataquality during 2002-2004, the the discontinuities in MERRA2 and ERA5 around late 2004 due to the MLS ozone data, a step-function proxy is added for the Jan. 2002-Sep. 2004 in the trend calculation. An extra step-function proxy is added in the MERRA2 MLR to remove the discontinuities associated with the transition from MLS v2.2 to v4.2 for 250-70 hPa for the period Jun. 2015-Dec. 2017. The trends are calculated for the period 2005-2017 using the MLR method same 2002-2017 using the same MLR method as for temperature (but with step function proxies in the reanalyses (Figure 15). SWOOSH and C3S ozone trends show good agreement in spacial distribution as well as magnitude in general (Figures 15a and b). From 250 to 100 hPa, ozone trends are mainly insignificant or opposite in sign by different data sets due to the large uncertainties of ozone data in this region. Asymmetry trends in two hemispheres, with significant decrease of ozone in NH mid-latitudes at 100-10 hPa and increase of ozone in SH mid-latitudes are found at 50-10 hPa. This is consistent with a recent study using the MLS ozone data (Chipperfield et al., 2018). At 100-50 hPa, ozone is decreasing in NH mid-latitudes ~~, which is also found by Steinbrecht et al. (2017) based on various ozone data sets of 2000-2016~~based on satellite data but positive or insignificant trend by reanalysis data.

~~Around 70 , unrealistic negative trends are found by MERRA2 data(Figure 15c), which are related with negative MERRA2 bias during 2015-2017. In contrast, stronger~~ Stonger positive trends in tropics and SH mid-latitudes and less negative trends in NH mid-latitudes are found by ERA5 data ~~from 50 to 20~~ at 30-20 hPa, which is ~~consequence of~~ related to the positive ERA5 bias during 2015-2017 in these regions (Figures ~~S1-S2). If the ozone trend is calculated for the period 2002-2017, the SWOOSH and C3S show similar spatial pattern (Figure S3) as seen in Figure 15. However, the MERRA2 and ERA5 show very different results (Figure S3c-d) as that in Figure 15.~~ S4).

Figure 16 shows the ozone trends from two model simulations as well as their differences. The ozone trends based on the model simulation with varying SST show similar trends as SWOOSH and C3S data. Insignificant trends are found at ~~200-100~~ 250-100 hPa in most regions. The maximum negative trends (~~-150~~ -100 ppbv/decade) located around ~~30~~ 25-20 hPa in NH mid-latitudes while the maximum positive trends at 10 hPa ~~around 20°S~~in tropics. While the SSTs are fixed to climatological values, ozone increases from the tropics to SH mid-latitudes in the middle stratosphere (30-10 hPa) and negative trends in the NH mid-latitudes from 100 to 10 hPa become much weaker (Figure 16b). The differences between these two runs, which indicate contributions from SSTs, show similar spacial pattern with the Transient run as well as observations. This confirms that dynamic processes are dominated for ozone trends in the middle stratosphere (100-10 hPa in NH and ~~30-10~~ 30-20 hPa in tropics~~and SH)~~), which is consistent with the previous study (Chipperfield et al., 2018). For the tropical lower stratosphere (20°S-20°N, ~~50-30~~ 70-30 hPa), ozone trends are determined by a combination of ODSs and SSTs (Figures 16b-c).

Considering the coupling between changes in ozone and temperature, the ~~tropospheric warming and decreases of ozone are related to SST changes~~ correlation coefficients between ozone and temperature anomalies for the period 2002-2017 are calculated. Consistent with previous studies (Abalos et al., 2012; Maycock, 2016; Gilford et al., 2016), observed ozone (GNSS RO) and temperature (SWOOSH) anomalies are highly correlated (>0.6) in the range from 100 to 20 hPa (Figure S5a). The correlation coefficients are highest in tropical region (~0.9). MERRA2 shows a similar correlation between ozone and temperature while the correlation in ERA5 is slightly weaker. Furthermore, we estimate a factor $b_f(p)$ between temperature and ozone anomalies at each grid point p by linear regression:

$$y(p,t) = b_f(p) \cdot x(p,t) \tag{2}$$

where $y(p,t)$ is monthly temperature anomalies and $x(p,t)$ is the monthly ozone anomalies at each grid point p. Then the potential contribution of ozone changes to temperature trends $T(p)$ are estimated by the ozone trend $O_3(p)$ and ~~subsequent~~

~~modulation of atmospheric circulation~~$b_f(p)$ with Eq. 3 (Figure 16d and Figure S6d).

$$T(p) = O_3(p) \cdot b_f(p) \quad (3)$$

While ozone and temperature are positively correlated, a decrease of ozone contributes to a cooling in the NH and in the tropical upper troposphere and mid-stratosphere. Increases of ozone lead to a warming effect in the SH and the lower stratosphere in the tropics.

Recall the question of the temperature trend attribution, the positive trends in the upper troposphere can be well explained by increases in SSTs (Figure 13). The stratospheric cooling, however, can not be fully explained. Satellite measurements show a stronger cooling in the SH than that in the NH. Model simulation and ozone-temperature correlations indicate that both SST and ozone changes contribute to a cooling in the NH but a warming in the SH. The exact reason for the strong cooling in the lower to mid-stratosphere in the SH awaits further studies. For the tropical warming in the lower stratosphere, it is related to both SST and ozone changes. As seen in Figure ~~S4~~ S6 SSTs are significantly increased during 2002-2017 almost globally except in the North Atlantic and the Southern Ocean. Such increase in SSTs would warm up the ~~atmosphere~~ troposphere and lead to strengthening in upward motion of the atmosphere, which ~~lifted more poor ozone lower tropospheric air to the upper troposphere and reduced ozone concentrations there. The enhanced upward motion could lead to cooling in temperature and less ozone in~~ leads to a cooling in the tropical lower stratosphere. ~~However, that is not the truth as seen in observations with temperature warming and ozone increase~~ At the same time, ozone is increased and contributes to a warming in that region (Figures ~~11 and 15) . This ozone increase should be partly related to the reduced emissions of ODSs since the Montreal Protocol, which contributes to~~ 16 and S5) . As indicated by Wang et al. (2015), the increase of temperature in the tropical lower stratosphere is dominated by an anomalous SST decline from 2001 to 2011. While a significant increase of SST occurs after 2011, the temperature in the ~~temperature warming in~~ tropical lower stratosphere ~~due to its radiative effects. The decreases in ODSs also partly lead to ozone increases in the middle stratosphere (Figure 15b). Note that the SST increases are asymmetry in the two hemispheres. SST increases are stronger and more significant in the NH than that in the SH. This leads to asymmetric changes of atmospheric circulation, e.g. the Brewer Dobson Circulation (BDC) in the stratosphere, and contribute to asymmetric distributions of temperature and ozone trends in the middle stratosphere (Figures 11 and 15)~~decreases and leads to a net cooling for the period 2002-2017. Ozone increases from 2002 to 2017 and contributes to a warming effect to the tropical lower stratosphere. However, the potential contribution of ozone to temperature in the tropical lower stratosphere is quite weak, which can not fully explain the observed warming in that region.

4 Conclusions and Discussion

The recent variability and trends of temperature in the UTLS have been studied for the period 2002-2017 using the high quality, high vertical resolution ~~GPS~~ GNSS RO data. The newest ERA5 reanalysis product, as well as the MERRA2 and the ERA-I reanalyses are evaluated for seasonal-to-interannual variations as well as linear trends of temperature in the UTLS. ~~While temperature is closely coupled with ozone, UTLS ozone from new and improved satellite data sets (SWOOSH and C3S) as well as the reanalyses (ERA5 and MERRA2) is analyzed to attribute recent temperature changes.~~

In general, all three reanalyses show good agreement with the ~~GPS~~ GNSS RO measurements for the annual cycle of temperature with consistent phase and comparable amplitude. However, relative large biases can be seen between reanalysis data set and ~~GPS~~ GNSS RO for the period ~~2001-2006~~2002-2006, which reveals an evident discontinuity of temperature time series in reanalyses. That is caused by the lack of observations and less constrained reanalysis data in the first stage and large amounts of data from the COSMIC satellite mission since 2007. Such discontinuity in reanalysis data should be carefully considered while using the reanalysis data analyzing trends. ERA5 ~~, as the newest generation of reanalysis from ECMWF, show obvious improvement refers to~~ shows obvious improvements of temperature data compared with ERA-I and ~~best agreement with GPS RO measurements~~ also a slight better agreement with GNSS RO measurements than MERRA2.

Temperature in the UTLS ~~performs~~ presents significant interannual variations which has been well known that are related to ENSO and QBO. Based on a multiple linear regression method, the relative contributions of ENSO and a pair of orthogonal time series of QBO (QBO50 and QBO30) are estimated from the ~~GPS~~ GNSS RO measurements as well as reanalysis data sets. Signals of ENSO and QBO show very good agreement between all three reanalyses and the ~~GPS~~ GNSS RO data, which indicates that the reanalyses are able to capture interannual variations of temperature in the UTLS.

~~Nearly 2 decades~~ 16 years of temperature data were analyzed by a MLR method to determine trends in the UTLS. A significant warming of 0.2-0.3 K/decade can be seen in most areas of the troposphere with stronger increase of 0.4-0.5 K/decade in mid-latitudes of both hemispheres. Contrast to the troposphere, the stratospheric temperature decreases at a rate of 0.1-0.3 K/decade~~except that in the lower most~~. Positive temperature trends are significant in the tropical lower stratosphere (100-50 hPa) ~~in the tropics and parts of mid-latitude in the NH, whereas the temperature trends are positive~~with a much weaker magnitude (0.1-0.5 K/decade) than that in a former period (2001-2011) as shown by a previous study (Wang et al., 2015). Again, ERA5 shows improved quality ~~compare~~ compared with ERA-I and ~~performs the best resemblance with the GPS RO data while insignificant warming trends exist~~ has the best agreement with the GNSS RO data in the three reanalyses. MERRA2 shows less significant warming trends in the tropical troposphere and too strong cooling ~~can be seen in MERRA2.~~ in its initial data but more consistent trends after the discontinuity corrections.

~~In the stratosphere, ozone distribution is highly correlated with the temperature change.~~ Similar with temperature data, reanalysis ozone are affected by the change of assimilated observations and methods. Negative trends of ozone are dominated in the NH at ~~150-100~~ 150-50 hPa. In the tropical lower stratosphere, increases of ozone are evident. Asymmetric trends of ozone can be found for the two hemispheres in the middle stratosphere, with significant ozone decrease in NH mid-latitudes and increases of ozone in SH mid-latitudes. Around the tropopause, trends are small and large differences between data sets are found. Further study and longer time series are needed for trend analyses in these regions. Overall, large biases exist in reanalysis and it is still challenging to do trend analysis based on reanalysis ozone data.

According to model simulations, the temperature increase in the troposphere as well as ozone decrease in the NH stratosphere could be mainly connected to the increase of SST and subsequent changes of atmospheric circulations. Ozone increases around ~~50~~ 20 hPa in the SH, decreases around 30 hPa and increases from 20 to 10 hPa in the tropics are also closely related to SST changes. This ~~support~~ supports the results of Chipperfield et al. (2018) which concluded that dynamical changes play an important role for the ozone variability in the ~~UTLS~~stratosphere. Ozone increases in the tropical lower stratosphere ~~are also~~

~~related to the reduced ODSs emissions~~ may related to reduced emissions of ODSs since the Montreal Protocol ~~. This increased ozone contributes to a temperature increase in this region due~~ (Polvani et al., 2017), and are partly offset by SST changes.

In the stratosphere, ozone and temperature variations are highly correlated with each other. Due to the radiative effects of ozone~~. Because of the decrease of ODSs emissions, stratospheric ozone seems to be recovery in the tropics as well as in SH~~, a decrease of ozone in the NH contributes partly to the temperature decrease in this region. The increased ozone may contribute to the temperature increase in the tropical lower stratosphere. However, ~~temperatures are decreased in this region. While the SST changes could not explain this neither, such stratospheric cooling could be related to GHGs increases and subsequent radiative cooling~~this contribution from ozone is relateively weak and can not fully explain the warming in that regions. In addition, it is partly offset by the cooling effect of increases in SSTs. The long-term trend of temperature in the lower stratosphere is strongly modified by interannual and decadal fluctuations related to natural processes like SST variations.

Recent temperature and ozone trends have been calculated by a MLR method based on observational data sets. However, trend assessments over short period of 1-2 decades are largely uncertain since the calculated trends are sensitive to start or end date (Santer et al., 2017). As RO data are acquired over longer periods with large number of observations (more than 10000 per day) by COSMIC2, the climate signal will emerge robustly and be more reliable for the temperature trends and variability studies in the UTLS.

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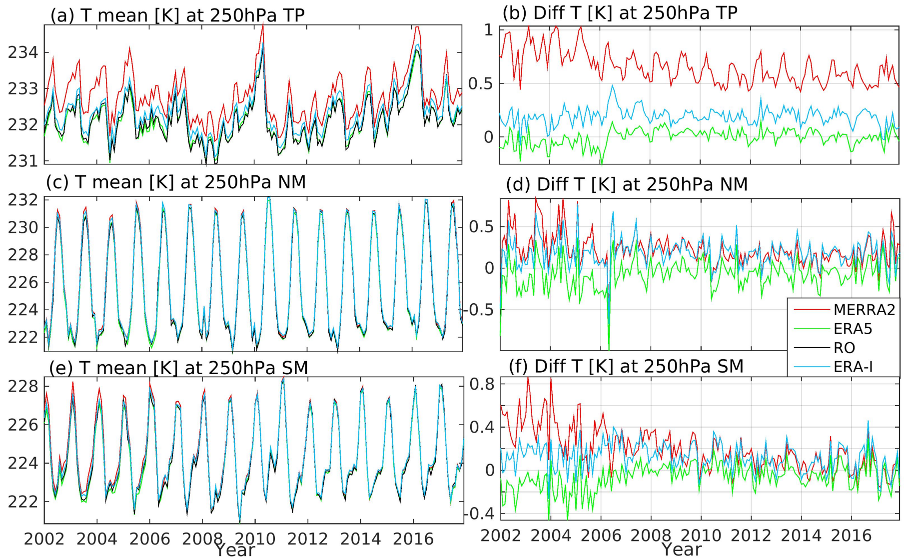

Figure 1. Left monthly mean temperature in K at pressure level ~~400~~ 250 hPa through three latitude bands of tropics (TP) (10°S-10°N)(a), northern mid-latitudes (NM) (25°N-45°N) (c), ~~NM~~southern mid-latitudes (SM) (25°S-45°S) (e); Right corresponding differences between ~~tree~~ three renanalyses and the ~~GPS~~ GNSS RO in figures (b), (d) and (e); Model with 103 levels (margin), ERA5 (green), ERA-I (light blue), MERRA2 (red) and ~~GPS~~ GNSS RO (black) are included.

~~Temperature trends in per Decade during different regions (SM: 25°S-45°S; NM: 25°N-45°N; TP: 10°S-10°N) from 250 to 10 for the period 2002-2017,* marked significant at 5% level. Levels 25015070502010SM_{GPSRO}0.31±0.13*0.41±0.16*0.22±0.19*-0.06~~

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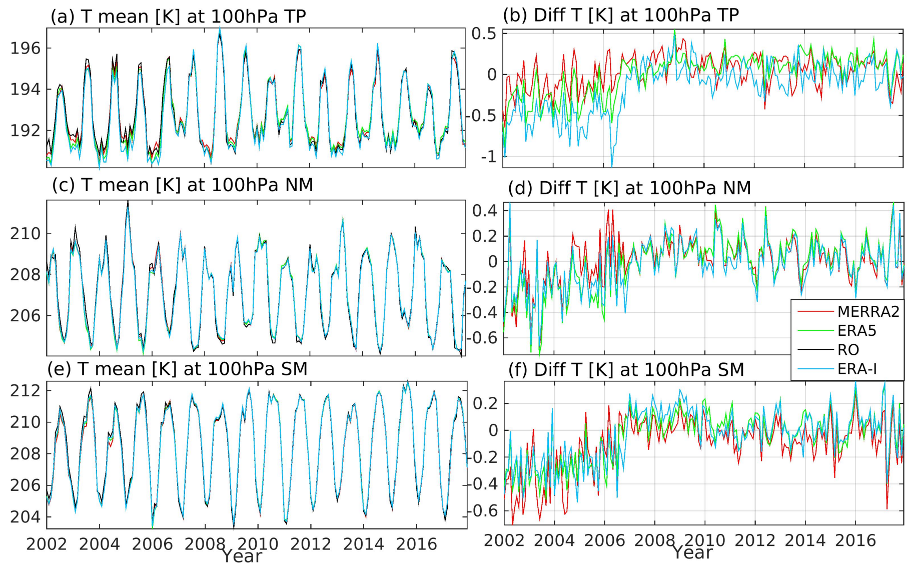

Figure 2. ~~Same as figure~~ As in Figure 1 ~~only~~ but for 100 hPa.

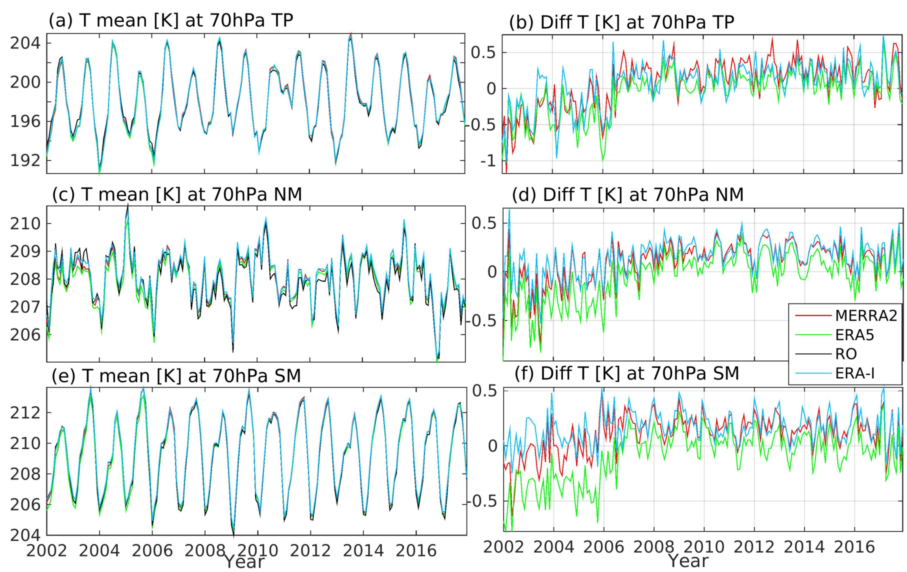

Figure 3. ~~Same as figure~~ As in Figure 1 ~~only~~ but for 70 hPa.

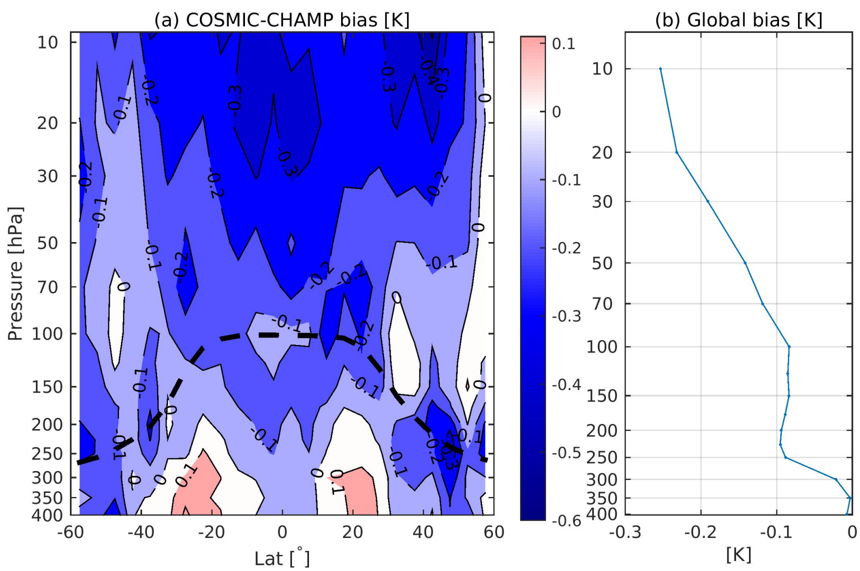

Figure 4. The bias in temperature climatology as retrieved from CHAMP and COSMIC RO data. The two ~~mission~~ missions obtained data during a 28 month overlap period from Jun. 2006 to Sep. 2008. (a) The difference of monthly zonal mean temperature; (b) The corresponding averaged difference for each layer. The dash black lines marked the tropopause height calcualted with GNSS RO data.

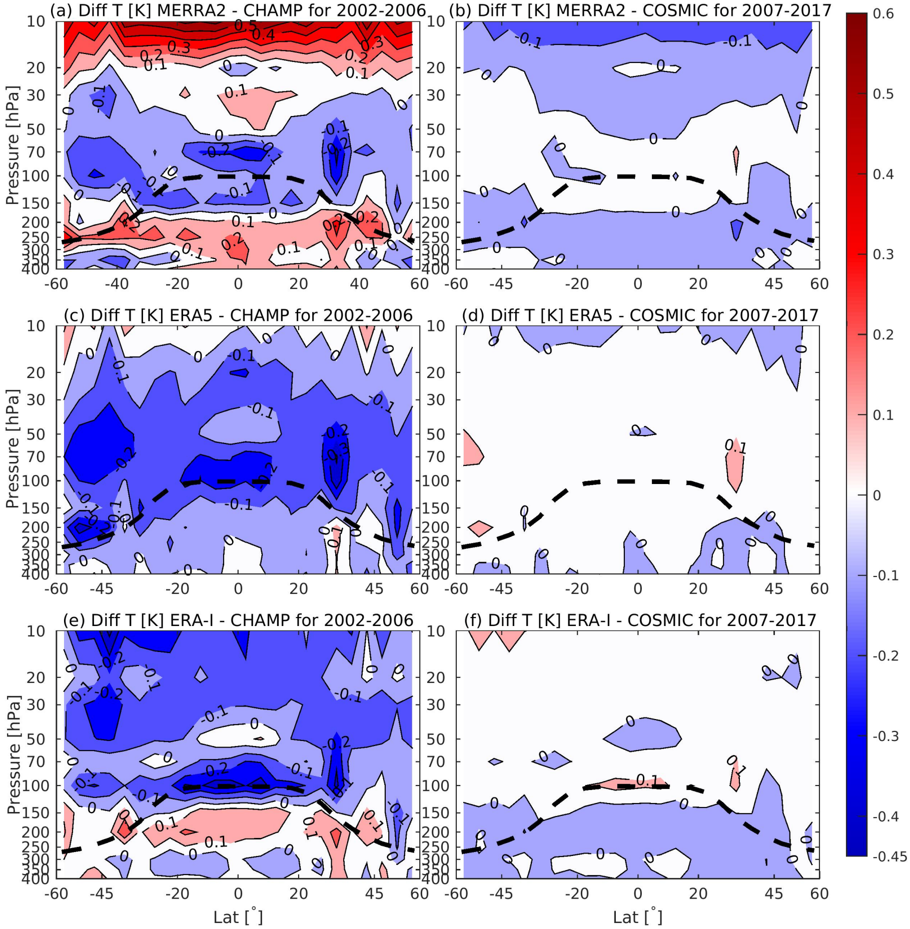

Figure 5. Differences of ~~mean~~ temperature anomalies between three reanalyses and CHAMP from 400 to 10 hPa for 2002-2006 (a, c and e) and between three renalayses and COSMIC for 2007-2017 (b, d and f). The dash black lines marked the tropopause height calcualted with GNSS RO data.

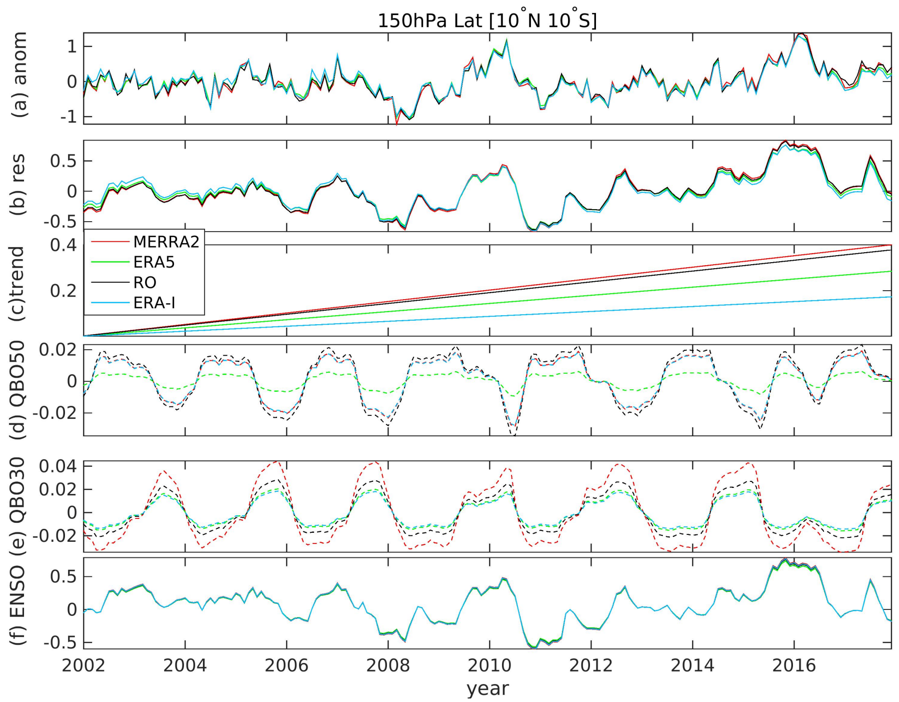

Figure 6. Temperature anomaly at pressure level 150 hPa in the tropics(10°S-10°N) from ERA5 (green), ERA-I (light blue), MERRA2 (red) and ~~GPS~~ GNSS RO (black) (a); (b) The corresponding residual; (c) The linear terms; (d) The QBO50 terms; (e) The QBO30 terms and (f) the ENSO terms; The solid lines in (c-f) marked the siginificant terms and the dash lines in (c-f) marked the insiginifcant terms.

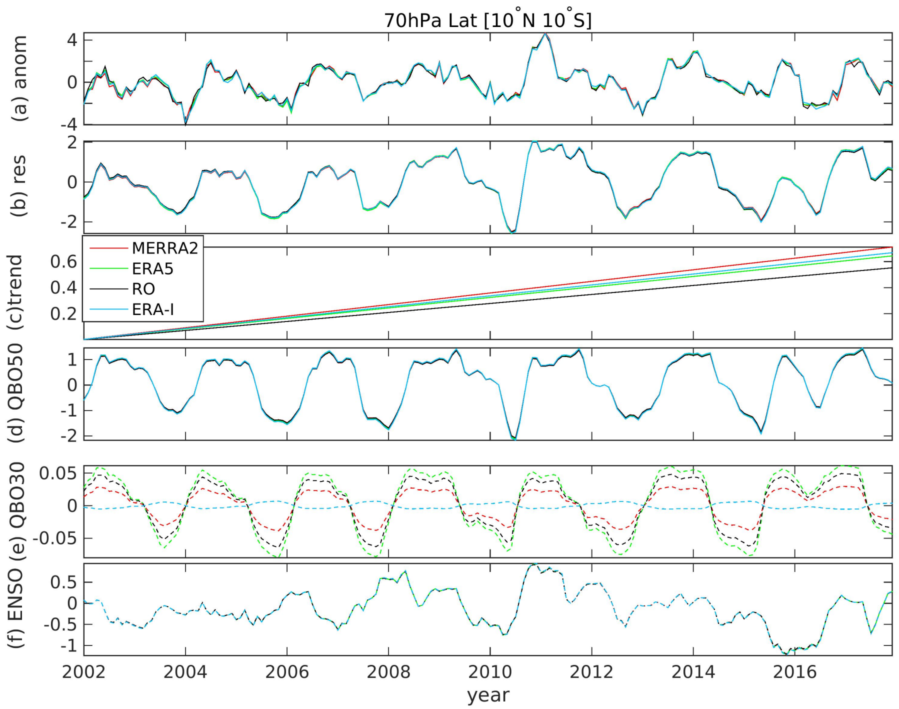

Figure 7. ~~Same as figure~~ As in Figure 6 ~~only~~ but for 70 hPa.

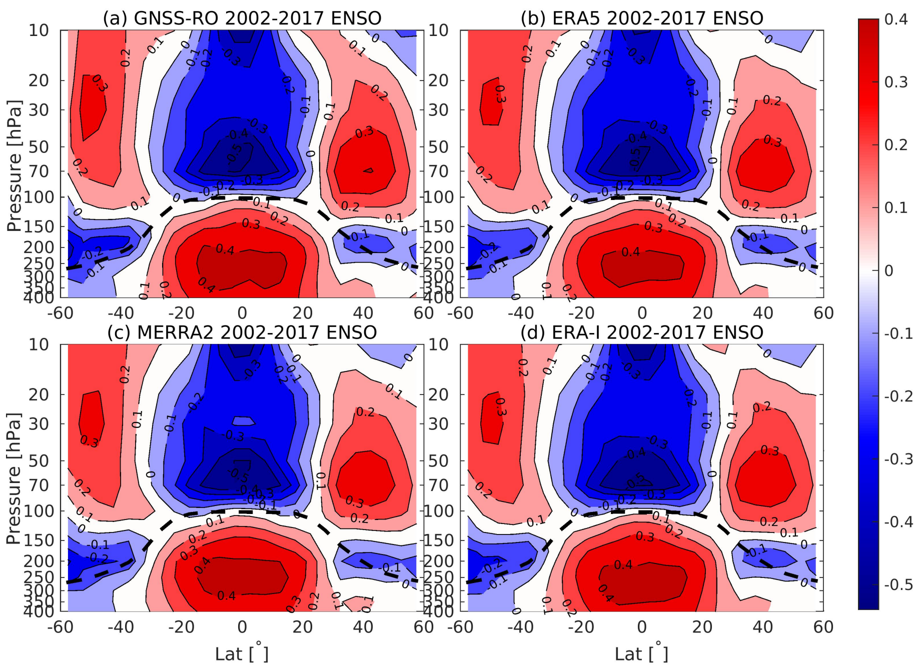

Figure 8. ENSO related temperature anomalies of ~~GPS~~ GNSS RO (a), ERA5 (b), MERRA2 (c) and ERA-I (d). The dash black lines marked the tropopause height calcualted with GNSS RO data.

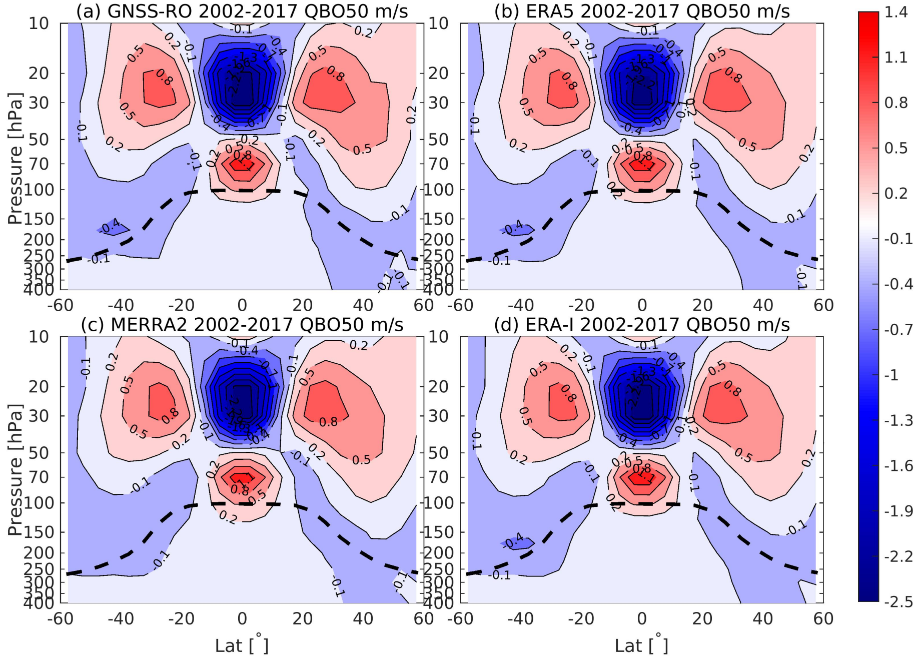

Figure 9. ~~Same as figure~~ As in Figure 8 but for QBO50.

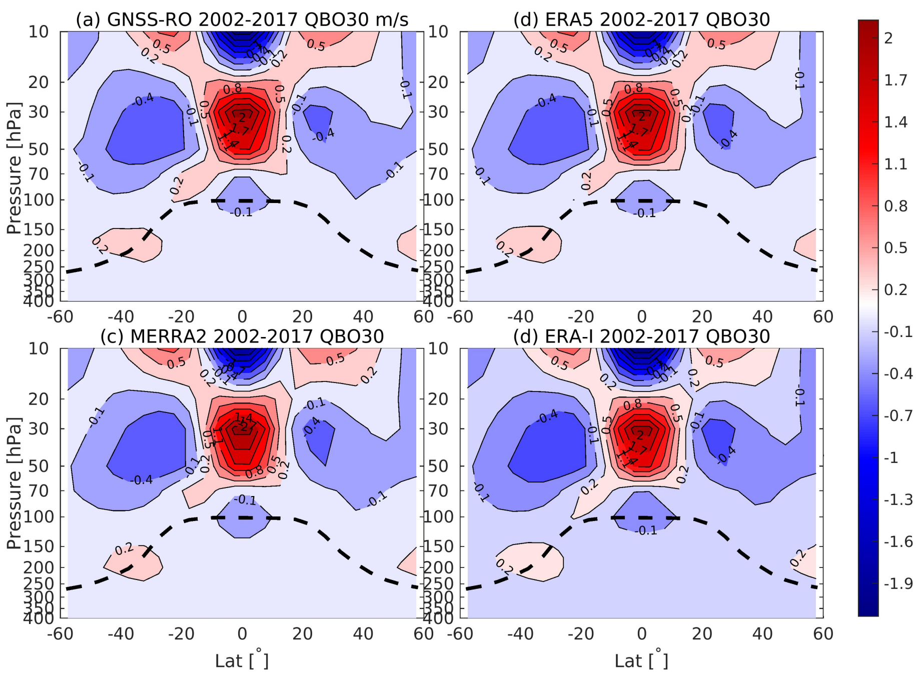

Figure 10. ~~Same as figure~~ As in Figure 8 but for QBO30.

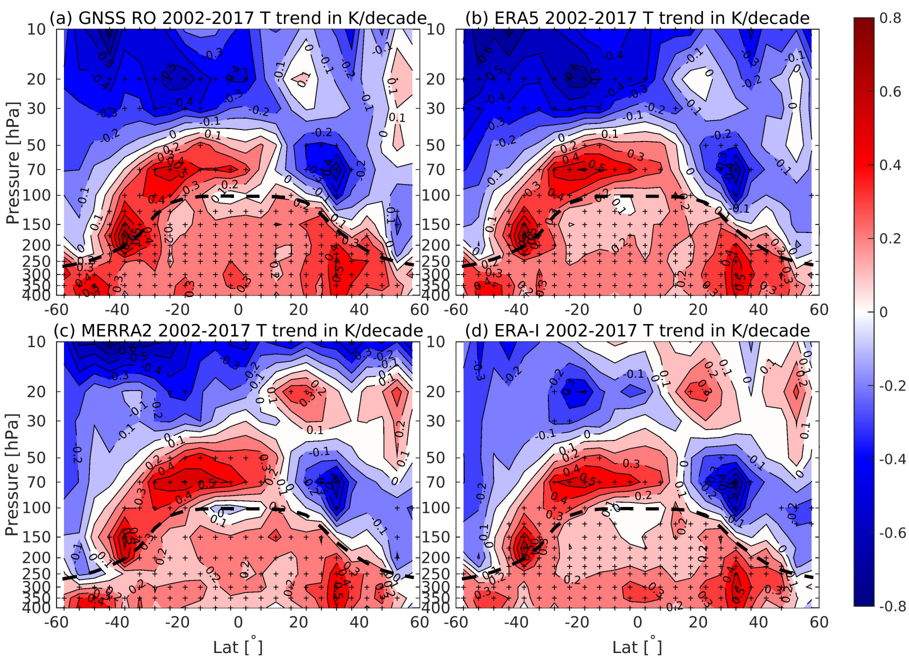

Figure 11. Temperature trend in $\mathrm{K/decade}$ based on ~~GPS~~ GNSS RO (a), ERA5 (b), MERRA2 (c) and ERA-I (d) data for period 2002-2017. The ~~green~~ '+' marked the significant area at ~~5~~95% level. The dash black lines marked the tropopause height calcualted with GNSS RO data.

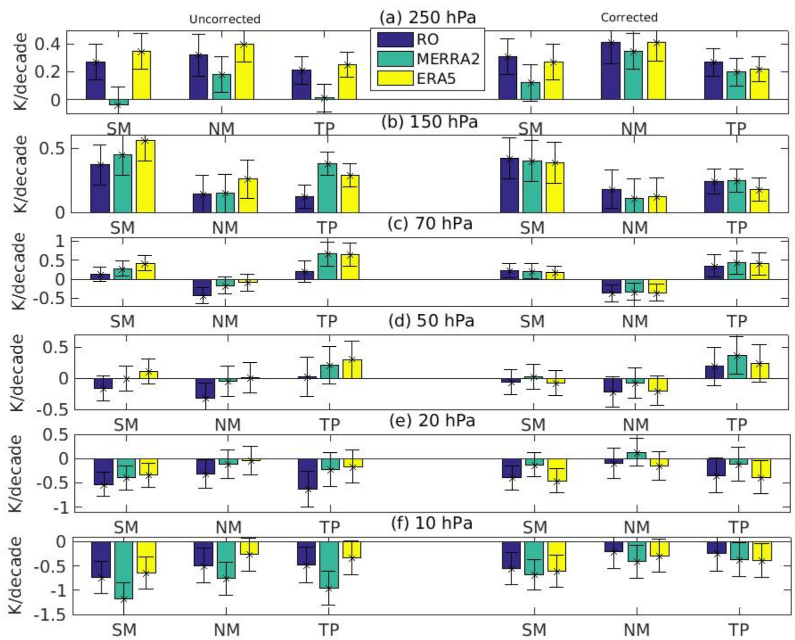

Figure 12. Estimated temperature trends in $\mathrm{K/decade}$ during different regions (SM: 25°S-45°S; NM: 25°N-45°N; TP: 10°S-10°N) from 2002 to 2017. (a-f) Trends in corrected and uncorrected data sets at 250, 150, 70, 50, 20 and 10hPa. Error bars represent 95% confidence intervals.

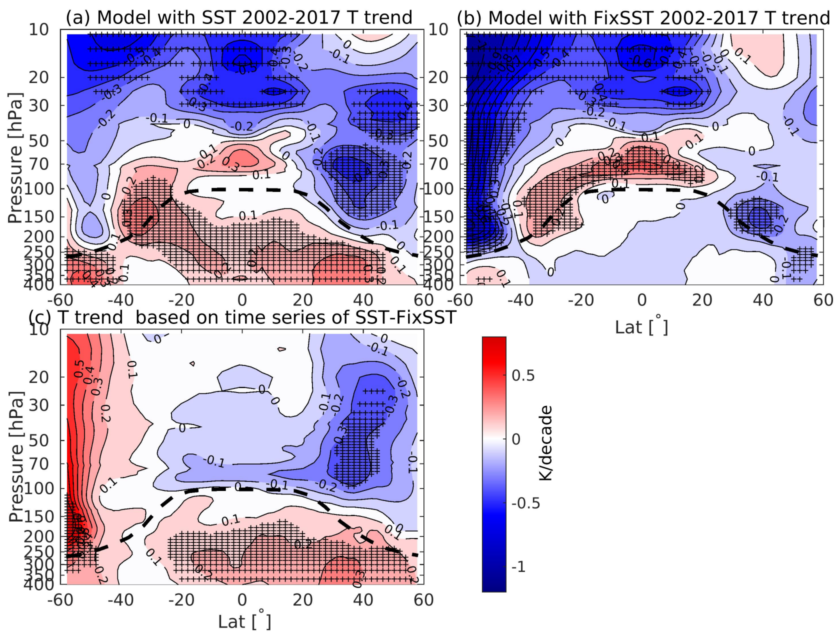

Figure 13. Temperature trend in K/decade based on model simulations with time varying SST (a), fixSST (b) and their differences (c) for period 2002-2017. The ~~green~~ '+' marked ~~the significant area at 5~~trends found to be more than 95% ~~level~~statistically significant. The dash black lines marked the tropopause height calcualted with GNSS RO data.

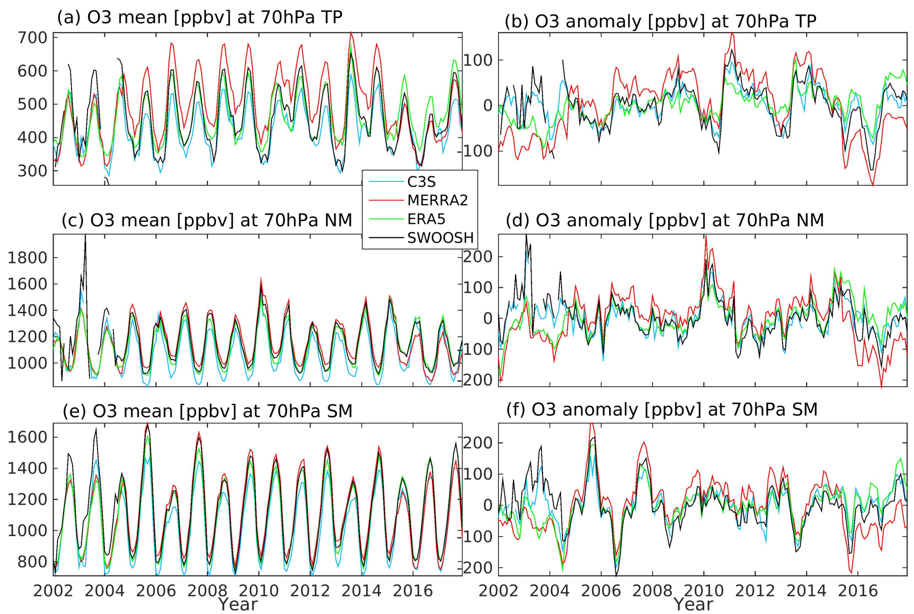

Figure 14. Left monthly mean ozone in ppbv at pressure level 70 hPa through three latitude bands of TP(10°S-10°N)(a), NM(25°N-45°N) (c), NM(25°S-45°S) (e); Right corresponding anomalies in figures (b), (d) and (e); Model with 103 levels (margin), ERA5 (green), C3S (light blue), MERRA2 (red) and SWOOSH (black) are included. The dash black lines marked the tropopause height calcualted with GNSS RO data.

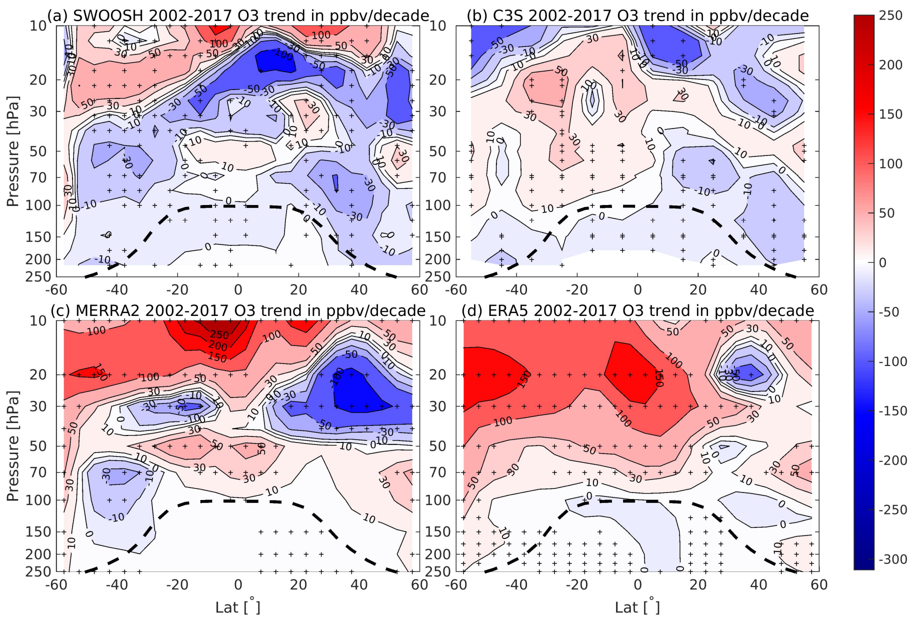

Figure 15. Ozone trend in ppbv/decade based on SWOOSH (a), ERA5 (b), MERRA2 (c) and C3S (d) data for period ~~2005-2017~~2002-2017. The ~~green~~ '+' marked ~~the significant area at 5~~trends found to be more than 95% ~~level~~statistically significant. The dash black lines marked the tropopause height calculated with GNSS RO data.

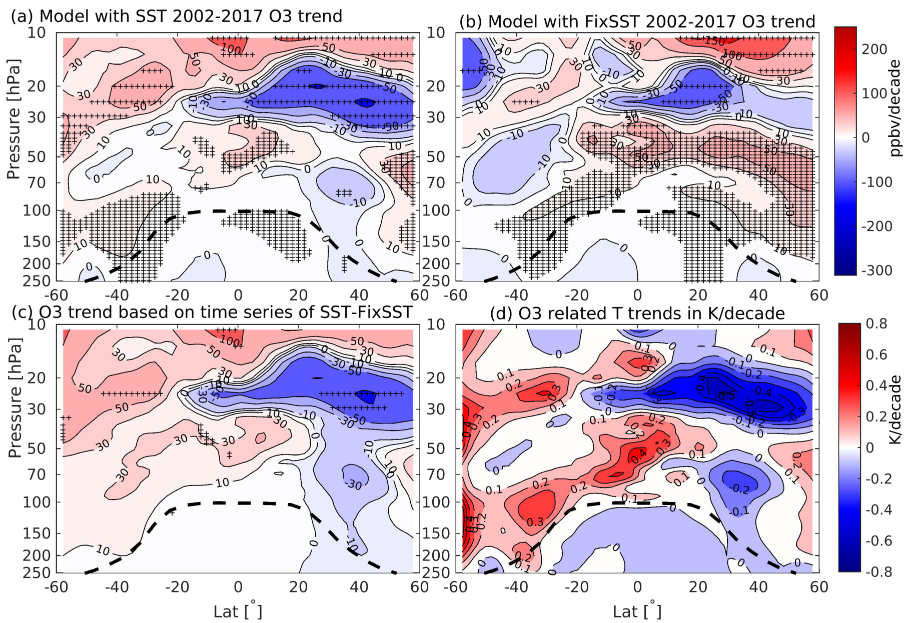

Figure 16. Ozone trend in ppbv/decade based on model simulations with time varying SST (a), FixSST (b) and thier differences SST-fixSST (c) for period 2002-2017. (d) Model ozone related GNSS RO temeprature trends in K/decade. The ~~green~~ '+' marked ~~the significant area at 5~~trends found to be more than 95% ~~level~~statistically significant. The dash black lines marked the tropopause height calcualted with GNSS RO data.