Responses to the comments by Referee #2

Manuscript number: acp-2021-647

Title: **Enhanced upward motion through the troposphere over the tropical western Pacific and its implications for the transport of trace gases from the troposphere to the stratosphere**

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The manuscript presents an analysis of atmospheric upward transport through the upper troposphere and lower stratosphere over the tropical West Pacific based on reanalysis data and model observations. Long-term changes in the upwelling are linked to increasing global sea surface temperatures leading to a strengthening of the Pacific Walker circulation and deep convection. Implications for stratospheric entertainment of CO and H2O are discussed.

The research question addressed here is an important one and the topic is of general interest to the readers of ACP. Some parts of the analysis are solid and provide valuable insights into long-term changes of the underlying processes. However, I have some major concerns (listed below) and recommend major revisions before the manuscript can be published.

Re: We thank for the reviewer's helpful comments. We have revised the manuscript thoroughly according to the comments and the manuscript has been improved substantially. The point-to-point responses are listed below.

Major comments

1) Caution is advised when using reanalysis data for trend detection as the quality and character of reanalyses may have changed over time and non-physical trends can result from changes in the observing system or execution stream. This has been demonstrated for many atmospheric quantities such as stratospheric temperature (Long et al., 2017, ACP) and residual circulation velocities (Chapter 5, S-RIP report, 2021).

Here, the trends derived from reanalysis are presented without any discussion of these aspects, but instead are used as if they would be reliable sources of long-term changes. A discussion of the limitations of reanalysis data for trend studies and words of caution are needed and the text should be changed accordingly throughout the manuscript, in particular when using reanalysis before 1979.

Re: We thank the reviewer for the very important comment. We totally agree with the reviewer that the limitations of reanalysis data for trend analysis should be discussed. Such discussion is added to the Section 2.

The text has been revised as: "A special caution is needed because of the limitations of reanalysis data. The reanalysis datasets assimilate observational data based on the ground- and space-based remote sensing platforms to provide more realistic data products. However, previous studies suggested that there are still uncertainties in the reanalysis data (e.g., Simmons et al., 2014; Long et al., 2017; Uma et al., 2021). The accuracy of the vertical velocity in reanalysis data sets has been evaluated by the Reanalysis Intercomparison Project (Fujiwara et al., 2017), which is initiated by the Stratosphere-troposphere Processes And their Role in Climate (SPARC). Results of a comparison between the radar observed data and the reanalysis data indicate that the updrafts in the UTLS are captured well near the TWP even though there are still large biases in the reanalysis datasets and the updrafts from the JRA55 data are stronger than those from the ERA5 and MERRA2 data (Uma et al. 2021). Additionally, discontinuities in the reanalysis data due to different observing systems (for example, transition from TOVS to ATOVS) may still exist (e.g., Long et al., 2017), which could lead to uncertainties in the long-term trend of a certain meteorological filed. Hitchcock (2019) suggested that the reanalysis uncertainty is larger in the radiosonde era (after 1958) than in the satellite era (after 1979), but the radiosonde era is of equivalent value to the satellite era because the dynamical uncertainty dominates in the both eras. The data in the radiosonde era (1958-1978) used in the present study may induce uncertainties in our results. Therefore, we discuss the trends for both the periods of 1958-2017 and 1980-2017. In addition, we combine three most recent reanalysis datasets (JRA55, ERA5, and MERRA2) to obtain relatively robust results."

The description about the trend analysis is also revised accordingly throughout the manuscript.

2) Trends of the vertical wind derived from the three reanalysis data sets agree in some regions but disagree in others as seen from Figure 2. A discussion of the level of agreement is needed. At the same time, it is not clear which region exactly is referred to as the tropical western Pacific (TWP). In many cases the authors would us the TWP in cases when the text and figures suggest that they refer to the Maritime Continent (e.g., ERA5 shows increasing trend of w over the Maritime Continent but decreasing trends over larger parts of the TWP). It would be very helpful, if the authors would define the regions upfront and use them consistently throughout the manuscript.

Re: Thanks for the comment. Some discussions about the trends of horizontal winds and vertical velocity in the JRA55, ERA5, and MERRA2 are added to the revised manuscript. The differences between the reanalysis datasets may be mainly due to the different time periods which are used to calculate the linear trends in JRA55 (1958-2017), ERA5 (1958-2017) and MERRA2 (1980-2017). An additional figure showing the trends of horizontal winds and vertical velocity in the JRA55, ERA5, and MERRA2 (Fig. R1) during 1980-2017 is added to the supplementary material (Supplementary Fig. 3). The discussion in the revised manuscript is expressed as:

"Such an enhancement of the upward motion over the TWP is evident in all three reanalysis datasets used here (JRA55, ERA5, and MERRA2), although there are also some differences between the three reanalysis datasets. For example, the trends of the horizontal winds in the upper troposphere in MERRA2 (Fig. 2c) are larger than those in JRA55 and ERA5 (Figs. 2a and b). There are negative trends of vertical velocity in JRA55 and ERA5 while positive trends of vertical velocity in MERRA2 over the northern Pacific (Figs. 2a-c). However, these differences are mainly due to the different time periods used to calculate the linear trends in JRA55 (1958-2017), ERA5 (1958-2017) and MERRA2 (1980-2017). Supplementary Fig. 3 gives the trends of *w* and horizontal winds in NDJFM during 1980-2017 using JRA55, ERA5, and MERRA2 data, which shows insignificant differences between these reanalysis

datasets. The trend patterns of the horizontal winds in JRA55, ERA5, and MERRA2 are consistent with each other (Supplementary Fig. 3). For the trends of vertical velocity, significant positive trends over the TWP region can be noted in the JRA55, ERA5, and MERRA2 datasets, although the trends in ERA5 are slightly weaker than those in JRA55 and MERRA2 (Fig. 2 and Supplementary Fig. 3). Comparing to the negative trends of the vertical velocity over the central Pacific in JRA55 and ERA5, the negative trends in MERRA2 extend more northward (Supplementary Fig. 3).”

The TWP region is defined as 20°S-10°N, 100°E-180°E. According to the referee’s comment, the TWP is marked using a black rectangle in the figures of revised manuscript.

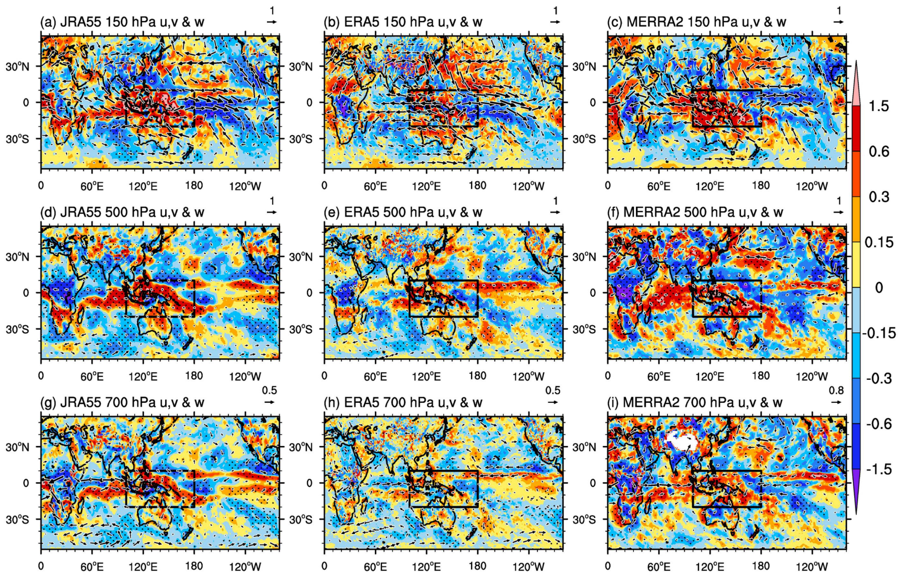

Fig. R1. The trends of the vertical velocity and horizontal winds in NDJFM using JRA55 (a, d, g), ERA5(b, e, h) and MERRA2(c, f, i) data during 1980-2017 at different levels. (a)-(c) are the trends of winds at 150 hPa. (d)-(f) are the trends of winds at 500 hPa. (g)-(i) are the trends of winds at 700 hPa.

3) It seems that the upwelling trends (averaged over the region of interest) are hardly significant even at the 90% confidence level. The uncertainty ranges and trend values need to be provided in the text or figure. Furthermore, it is not clear why the

averaging is done over 20S-10N. Looking at Figure 2, my impression is the averaging over 20S-20N will not result in trends significant at the 90% confidence level. If this is the case, it should be stated in the text.

Re: The uncertainty ranges and trend values are shown in the revised manuscript. "The intensity of the upward motion over the TWP at 150 hPa increased 3.0±1.2×10^8 kg s^{-1} $decade^{-1}$ (8.0±3.1% $decade^{-1}$), 1.3±1.2×10^8 kg s^{-1} $decade^{-1}$ (3.6±3.3% $decade^{-1}$), and 3.0±2.8×10^8 kg s^{-1} $decade^{-1}$ (7.5±7.1% $decade^{-1}$) in JRA55, ERA5, and MERRA2 data, respectively. As shown in Figs. 3b and c, the intensity of the upward motion at 500 hPa and 700 hPa in JRA55 and the intensity of the upward motion at 500 hPa in ERA5 over the TWP also increased significantly at 95% confidence level (4.6±2.6×10^8 kg s^{-1} $decade^{-1}$, 2.9±1.7×10^8 kg s^{-1} $decade^{-1}$, and 2.5±2.5×10^8 kg s^{-1} $decade^{-1}$, respectively). The increasing trends of the intensity of the upward motion at 700 hPa in ERA5 and at 500 hPa and 700 hPa in MERRA2 are significant at the 90% confidence level at rates of 1.9±1.6×10^8 kg s^{-1} $decade^{-1}$, 5.4±5.3×10^8 kg s^{-1} $decade^{-1}$ and 3.9±3.8×10^8 kg s^{-1} $decade^{-1}$, respectively. "

The description about how to calculate the uncertainty ranges is also added to the Section 2 as:

"The linear trends are estimated using a simple least square regression method. The significances of the correlation coefficients, mean differences, and trends are determined via a two-tail Student's t-test. The confidence interval of trend is calculated using the following equation (Shirley et al., 2004):

$$\left(b - t_{1-\frac{\alpha}{2}}(n-2)\sigma_b, b + t_{1-\frac{\alpha}{2}}(n-2)\sigma\right)$$

where b is the estimated slope, σ **denotes the standard error of the slope, and** $t_{1-\frac{\alpha}{2}}(n-2)$ **represents the value of t-distribution with the degree of freedom**

equal to *n*-2. α is the two-tailed confidence level. σ is calculated as: $\sigma = b\sqrt{\frac{\frac{1}{r^2}-1}{n-2}}$.”

The averaging is done over 20°S-10°N because of two reasons: 1. The center of upward motion in the boreal winter (NDJFM) over the tropical western Pacific is mainly located in the region over 20°S-10°N. 2. The intensification of upward motion over the tropical western Pacific is more significant over 20°S-10°N. To avoid confusion, some explanations are added to the revised manuscript.

The confidence level of significance of the trend analysis could be impacted by the fluctuations in the time series. The other referee pointed out that there are extreme minima in the time series of the upward motion over the TWP (Fig. 3), which are mainly due to the ENSO events. Here, the time series of the upward motion over the TWP with the ENSO signal removed using the single linear regression method are also shown (Fig. R2). It could be seen that the extreme minima become much weaker after removing the ENSO signal using the linear regression method. This result suggests that the El Niño events could affect the upward motion over the TWP and to a large extent result in the extreme minima (1982, 1991, and 1997). After removing the large fluctuations due to the ENSO events, the upward motions over the TWP at 150 hPa, 500 hPa, and 700 hPa in NDJFM in JRA55, ERA5, and MERRA2 show statistically significant intensifying trends above the 95% confidence level.

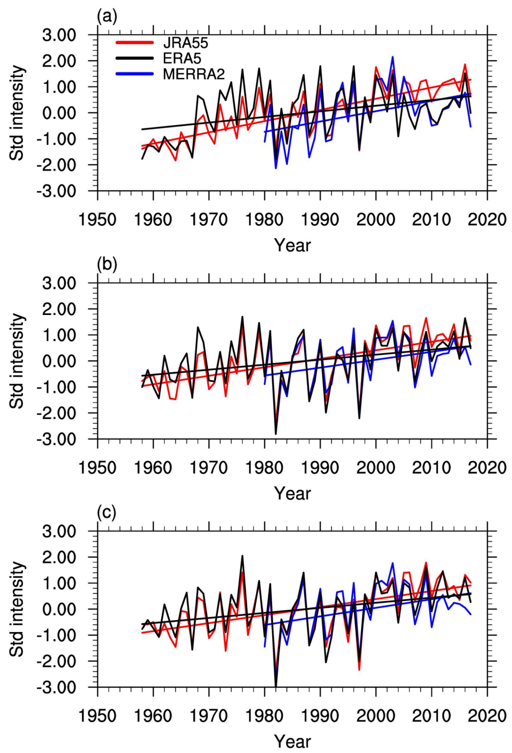

Fig. R2. The time series of the standardized intensity of the upward motion over the tropical western Pacific (20°S-10°N, 100°E-180°E) at (a) 150 hPa; (b) 500 hPa; and (c) 700 hPa extracted from JRA55 (red), ERA5 (black) and MERRA2 (blue) datasets after removing the ENSO signal using linear regression method. The straight lines in each figure indicate the linear trends. The linear trends of the upward motion intensity over the TWP at 150 hPa, 500 hPa, and 700 hPa from three datasets are statistically significant at the 95% confidence level.

4) Where is the cold point temperature trend coming from (Figure 4)? This data source is not listed in the text or caption. Given that it starts at 1958, most likely the trend is derived from JRA55. Again, some words of caution are needed, given that cold point temperature trends from reanalysis data sets can show significant differences even for the satellite period (Tegtmeier et al., 2020, ACP).

Re: We thank for the referee's comment. The trend of CPTT in Fig. 4 is from JRA55 data. The data source is added to the figure caption in the revised manuscript. Caution is added to the revised manuscript as: "It should be noted that the CPTT from different reanalysis datasets may show different trends even

for the satellite period (Tegtmeier et al., 2020). Additionally, the JRA55 data before 1978 may also lead to uncertainties in the CPTT trends. Caution is needed when discussing the trends of CPTT from reanalysis datasets."

5) The discussion of the trends of stratospheric upwelling needs to refer to Chapter 5 of the SPARC S-RIP report. Chapter 5 states in its abstract: 'However, estimates of long-term trends in tropical upwelling are inconsistent among different products, showing either strengthening, weakening, or no trend.' Therefore, results shown in Figure 11 based on JRA55 are most likely not consistent with other reanalyses.

Re: We thank the referee's comment. The discussion of the trends of stratospheric upwelling is rewritten. The trends of stratospheric upwelling in ERA5 and MERRA2 are added to the supplementary material (Fig. R3). The discussion is written as:

"The tropical upwelling of BDC (w^*) which calculated using the TEM formula increased significantly in the lower stratosphere over past decades as seen in the JRA55 data and the Control simulation (Figs. 12a and 12b). We found that the 70 hPa upward mass flux in NDJFM in the tropics (15°S-15°N) increased 2.8±1.9% decade^{-1} (significant at the 95% confidence level) in the JRA55 data from 1958 to 2017 (Fig. 12a) and 4.6±4.3% decade^{-1} (significant at the 95% confidence level) in the MERRA2 data from 1980 to 2017 (Supplementary Fig. 7b). From the ERA5 data, the 70 hPa upward mass flux in NDJFM increased in the north hemisphere (0-15°N) at a rate of 5.0±2.8% decade^{-1} (significant at the 95% confidence level), but decreased significantly in the south hemisphere (0-15°S) during 1958-2017 (Supplementary Fig. 7a). On average, the trend of the 70 hPa upward mass flux in NDJFM in the tropics (15°S-15°N) is insignificant in ERA5. In fact, many previous studies have investigated the trends of BDC. For example, Abalos et al. (2015) investigated the trends of BDC using JRA55, MERRA, and ERA-Interim data during 1979-2012 and suggested that the BDC in JRA55 and MERRA significantly strengthened throughout the layer 100-10 hPa of order 2-5% decade^{-1}, while the BDC in

ERA-Interim shows weakening trends. Diallo et al. (2021) compared the trends of the BDC in the ERA5 and ERA-Interim during 1979-2018 and pointed out that the BDC in the ERA-Interim shows weakening trend and the BDC in the ERA5 strengthened 1.5% decade^{-1} which is more consistent with other studies. In the present study, we only focus on the trend of the BDC in the wintertime (NDJFM) in the tropics (15°S-15°N) during 1958-2017, which may lead to some differences between our result and that in the previous studies. Overall, the trends of the tropical upwelling of BDC derived from JRA55, MERRA2 data and the Control simulation are similar to that in previous studies using both reanalysis datasets and model results (e.g., Butchart et al., 2010; Abalos et al., 2015; Fu et al., 2019; Rao et al., 2019; Diallo et al., 2021). However, the tropical upwelling of the BDC decreased in ERA5 data in the tropics (15°S-15°N), which are different from the results in JRA55 and MERRA2. ”

“In summary, the tropical upwelling of the BDC is likely strengthened as shown in JRA55 and MERRA2 reanalyses as well as model simulations, although there are some uncertainties since the ERA5 data show a negative trend. This may impact on the transport of the tropospheric trace gases from the TTL to a higher altitude. The increased concentration of CO in the UTLS in Fig. 8c and 10f may be due to a combined effect of the strengthened tropical upwelling of the BD circulation and the enhanced upward motion over the TWP.”

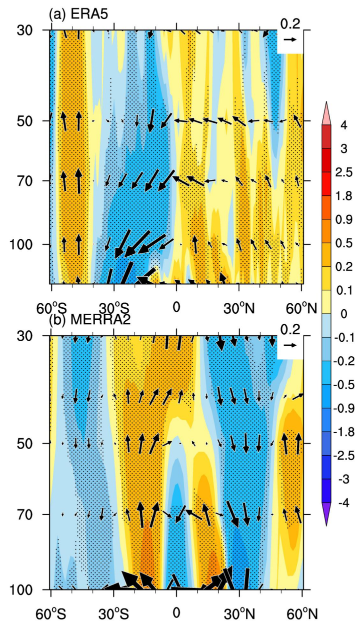

Fig. R3. The trends of the BD circulation calculated using the TEM formula in ERA5 and MERRA2. (a) The trends of w* (10^{-5} m s^{-1} a^{-1}) and v* (10^{-2} m s^{-1} a^{-1}) in NDJFM during 1958-2017 using ERA5 data. (b) The trends of w* (10^{-5} m s^{-1} a^{-1}) and v* (10^{-2} m s^{-1} a^{-1}) in NDJFM during 1980-2017 using MERRA2 data.

6) I don't agree with the interpretation the CO changes based on various model runs as presented in Figure 9. Both simulations have the same sources and the control run shows enhanced convective uplifting brining more CO to higher altitudes. For the tropical West Pacific, the trends are larger for the Control run throughout the whole vertical extent of the troposphere. However, enhanced upwelling would result in a less strong trend at the surface and boundary layer, opposite to what the simulations indicate here. In fact, some recent studies showed that over the Indian Ocean, CO abundance in the boundary layer decreases (despite the growing sources) while it increases in the mid to upper troposphere due to enhanced convective activity (e.g., Girach and Nair, 2014). The discussions and conclusions regarding this figure need to be revised.

Re: We thank for the referee's comment. According to the referee's comment, the reason for the increasing trends of CO in the lower troposphere shown in Fig. 9f is further investigated. The trends of CO in the lower troposphere using the

Control and Fixsst simulations as well as the difference between them are shown (Fig. R4). The trends of difference of horizontal winds at 925 hPa between the Control and Fixsst simulations are also shown (Fig. R4c). It can be found that there are northerly trends over east Asia and northeasterly trends near the south Asia (Fig. R4c), which suggests that more CO-rich air from east Asia and south Asia could be transported to the TWP in the Control simulation comparing to the Fixsst simulation. Since the CO concentration at 900 hPa over the northern Pacific is higher than that over southern Pacific (Fig. R5), the northerly trends over the western and central Pacific may also contribute to the increased CO in the lower troposphere over the TWP in Fig. 9f. The interpretation about the Fig. 9 is revised in the revised manuscript as:

"It should be mentioned that the increasing trends of CO in the lower troposphere in Fig. 10f may be mainly caused by the changes in the horizontal winds. Girach and Nair (2014) suggested that enhanced deep convection and the subsequent intensified upward motion may lead to a decreased CO concentration in the lower troposphere and an increased CO concentration in the upper troposphere. The trends of horizontal winds at 925 hPa are shown in Supplementary Fig. 8c. There are northerly trends over east Asia and northeasterly trends near the south Asia (Supplementary Fig. 8c), which suggests that more CO-rich air from east Asia and south Asia could be transported to the TWP in the Control simulation comparing to the Fixsst simulation. Since the CO concentration in the lower troposphere over the northern Pacific is higher than that over southern Pacific, the northerly trends over the western and central Pacific may also contribute to the increased CO in the lower troposphere over the TWP in Fig. 10f."

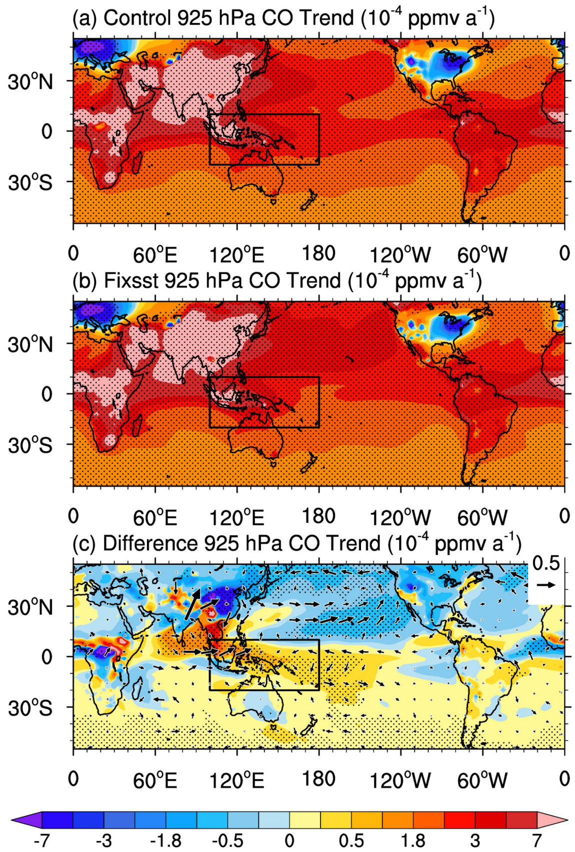

Fig. R4. The trends of CO (10^{-4} ppmv) at 925 hPa in NDJFM during 198-2017 in the (a) Control simulation, (b) Fixsst simulation, and (c) the difference between the Control and Fixsst simulations. The vectors in (c) denote the trends of the difference of 925 hPa horizontal winds (10^{-1} m s^{-1}) between the Control and Fixsst simulations.

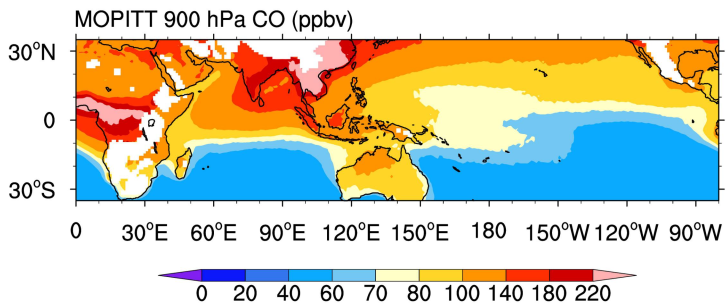

Fig. R5. The climatological mean CO concentration at 900 hPa in NDJFM during 2000-2017 using MOPITT data.

Minor comments

Should the title say '… implications for …'?

Re: Corrected.

For the fact that halogenated gases are enhanced over the WP, a citation is needed. The citations given at the end refer to tropospheric halogen chemistry. What is meant with the second part of the sentence? A general statement, that halogens impact stratospheric ozone chemistry? Or that halogens injected over the West Pacific have a relatively large impact on stratospheric ozone chemistry?

Re: We thank for the referee's comment. Citations are added to the revised manuscript. The sentence is rewritten according to this comment and the comment of the other referee as:

"Through the TWP region, tropospheric trace gases, e.g., the natural maritime bromine-containing substances and outflow from anthropogenic emissions from South Asia, are lifted to the upper troposphere and lower stratosphere (UTLS) by the strong upward motion and the deep convection and subsequently into the stratosphere by the large-scale upwelling (e.g., Levine et al., 2007, 2008; Navarro et al., 2015), which affects the ozone concentration and other chemical processes in the stratosphere (e.g., Feng et al., 2007; Sinnhuber et al., 2009)."

Line 190: What is an intensifying trend? A trend increasing over time?

Re: Sorry for the confusing. It should be a positive trend, not an intensifying trend. We have corrected the sentence in the revised manuscript.

Line 272: figure 2f shows wind fields at 500 hPa. Do you mean a different figure here?

Re: We are sorry for the mistake. It should be Figure 4d here. The mistake is corrected in the revised manuscript.

Line 270-274: This line of argumentation doesn't make any sense to me, and it is not clear what the authors are trying to say.

Re: We are sorry for the confusion. The sentence is rewritten as:

"As suggested by the correlation coefficients between the upward motion at 150 hPa over the TWP and SSTs in Fig. 4d, warmer SSTs over the tropical central and eastern Pacific, and Indian Ocean may lead to a weakened upward motion over the TWP (negative correlation). The warming trends of SSTs over the eastern maritime continent and tropical western Pacific may result in an intensification of the upward motion over the TWP."

Nearly all figures are too small, and the captions are very hard to read.

Re: The figures are enlarged and the captions are rewritten.

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