Responses to the comments by Referee #1

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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December 2021

This is an interesting and useful study. However the scientific content, the quality of the study and its presentation should be improved. In particular, the text is in some parts very descriptive and technical. I suggest some major revisions before publication by ACP.

Re: Thank you very much for your helpful suggestions which help us improve our manuscript substantially. We have modified our manuscript according to the comments. Our point-to-point responses to the reviewer' s comments are below:

General comments:

1) In general in the manuscript it is very often written 'we found a positive or negative trend'. Please specify here your message by adding some numbers in the text (a trend of xxx per year or a change of xxx within 60 years from 1958 to 2017). It would be also very helpful to give the reader an impression whether these trends are of minor or major importance by adding some numbers from the literature for comparison. In general, I am wondering that the results are not discussed more quantitatively (see specific comments below). Further, please explain in detail how the trends are calculated and how the El Niño Southern Oscillation (ENSO) is considered in calculating the trends.

Re: We thank the reviewer for the constructive comments. The quantitative results are added to the revised manuscript according to the referee's specific comments below. The methods of how the trends are calculated and how the impact of ENSO is evaluated are also described in the revised manuscript. The details are shown in the responses to the referee's specific comments below.

2) Figures: In general, the font size of the labels is very small and should be enlarged. Further, the text in the figure captions is very similar to each other. Please give here the reader more information which data or model simulations are shown and add some explanation what is important or what is the main message of the figure.

Re: Thanks for the suggestion. The font sizes of the labels in each figure are enlarged, and the figure captions are rephrased.

3) In Section 2 the used data sets and model simulations are described. However, I am missing a bit more motivation for the reader to understand why these data sets and model simulations are used. A bit more explanation would be helpful.

Re: Thanks for the comment. We have added some text to explain why the datasets and model simulations are used in this study, and the descriptions about the reanalysis datasets and model simulations are rephrased according to the referee's specific comments.

3) The use of observations such as CO satellite measurements would strengthen the main message of the manuscript. Therefore, I recommend to add some satellite data (e.g. MLS CO https://mls.jpl.nasa.gov/eos-aura-mls/data-products/co)

Re: We thank the reviewer's good suggestion. An extra figure showing the trends of CO observed by MOPITT and MLS at near 200 hPa during 2000-2017 and 2005-2017 is added in the revised manuscript. The CO shows significantly increasing trends over the TWP in NDJFM using MOPITT (at 200 hPa during 2000-2017) and MLS data (at 215 hPa during 2005-2017). The MLS CO data show that the area-averaged CO increased approximately 2.0±3.7 ppbv decade^{-1} over the TWP, while the CO increased 5.0±3.1 ppbv decade^{-1} near the equator, 150°E at 215 hPa in NDJFM during 2005-2017 (Fig. R1). The area-averaged MOPITT CO data increased at a rate of 5.0±3.1 ppbv decade^{-1} at 200 hPa over the TWP in NDJFM during 2000-2017. It should be pointed out that the linear trends of CO are calculated based on the satellite data which only cover 14 or 18 years due to the data limitation here. Hence, the linear trends of CO may have uncertainties particularly in the regions with large interannual variations in CO. To partially overcome this shortage, the trends of MLS CO at 215 hPa during

time periods of 2005-2016, 2006-2016, 2006-2017, and 2007-2016 and the trends of MOPITT CO at 200 hPa during time periods of 2000-2016, 2001-2016, 2001-2017, and 2002-2016 are shown in Fig. R2 (Supplementary Fig. 6). It could be found that the CO near 200 hPa shows robustly increasing trends over the TWP in satellite data (both of MLS and MOPITT). Overall, though the observed CO only covers less than 20 years, the results from the satellite data may provide extra evidence for the impact of the positive trends of upward motion over the TWP on the trace gases in the upper troposphere. The above discussion is added to the revised manuscript. We hope these results may further support our main conclusions in this study.

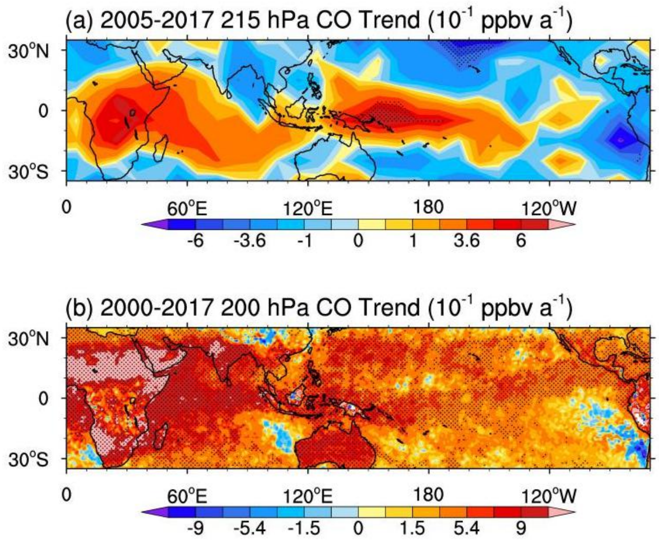

Fig. R1. The trends of CO derived from the MLS and MOPITT data. (a) The trends of CO (10^{-1} ppbv a^{-1}) at 215 hPa using MLS data in NDJFM during 2005-2017. (b) The trends of CO (10^{-1} ppbv a^{-1}) at 200 hPa using MOPITT data in NDJFM during 2000-2017. The trends of CO over the dotted region are statistically significant at the 90% confidence level.

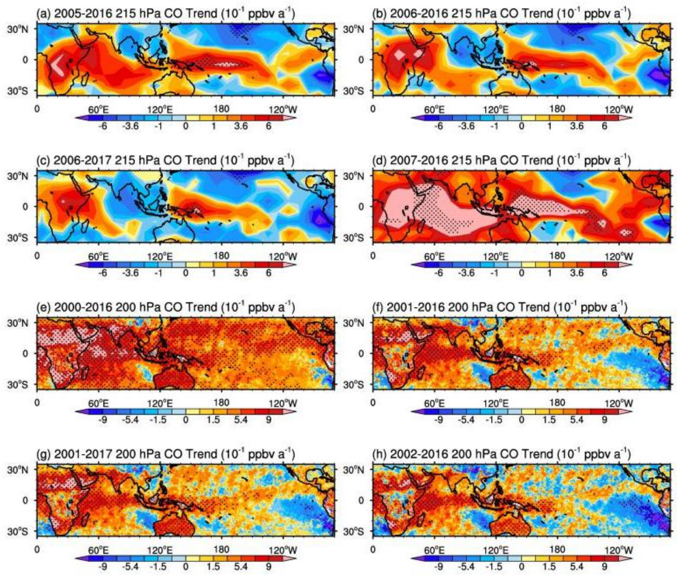

Fig. R2. The trends of CO derived from the MLS and MOPITT data. (a)-(d) The trends of CO (10^{-1} ppbv a^{-1}) at 215 hPa using MLS data in NDJFM during periods of (a) 2005-2016; (b) 2006-2016; (c) 2006-2017; and (d) 2007-2016. (e)-(h) The trends of CO (10^{-1} ppbv a^{-1}) at 200 hPa using MOPITT data in NDJFM during periods of (e) 2000-2016; (f) 2001-2016; (g) 2001-2017; and (h) 2002-2016. The trends of CO over the dotted region are statistically significant at the 90% confidence level.

Specific Comments:

P2 L2: 'A significantly intensified upward motion through the troposphere over the TWP in the boreal wintertime (November to March of the next year) has been detected.' Please make this statement more quantitative.

Re: Corrected. The phrase is rewritten as: "A significantly intensified upward motion through the troposphere over the TWP in the boreal wintertime (November to March of the next year, NDJFM) has been detected using multiple reanalysis datasets. The upward motion over the TWP is intensified at rates of 8±3.1% decade^{-1} and 3.6±3.3% decade^{-1} in NDJFM at 150 hPa from 1958 to 2017

using JRA55 and ERA5 reanalysis datasets, while the MERRA2 reanalysis data show a 7.5±7.1% decade^{-1} intensified upward motion for the period 1980-2017.”

P2 L18: Please specify here which reanalyses are used.

Re: Added.

P2 L23: 'numerical simulation' --> 'simulation with WACCM4' ?

Re: Updated.

P2 L24: 'show that more CO could be elevated to the tropical tropopause layer (TTL)' Please make this statement more quantitative.

Re: Rephrased as: “Using CO as a tropospheric tracer, the WACCM4 simulations show that an increase of CO at a rate of 0.4 ppbv decade^{-1} at the layer 150-70 hPa in the tropics is mainly resulted from the global SST warming and the subsequent enhanced upward motion over the TWP in the troposphere and strengthened tropical upwelling of Brewer-Dobson (BD) circulation in the lower stratosphere.”

P2 L27: Why is aerosol explicitly emphasized here. Please clarify (e.g. outflow from polluted air from South Asia?)

Re: We thank the reviewer’s comment. This sentence has been rewritten as: “This implies that more tropospheric trace gases and aerosols from both natural maritime source and outflow from polluted air from South Asia may enter the stratosphere through the TWP region and affect the stratospheric chemistry and climate.”

P3 L42: Please add possible sources of ozone-depleting halogen-containing substances in TWP (outflow from anthropogenic emissions from South Asia, natural maritime bromine-containing substances?).

Re: We thank the reviewer's comment. This sentence has been rewritten 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 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 affect the ozone concentration and other chemical processes in the stratosphere (e.g., Feng et al., 2007; Sinnhuber et al., 2009)."

P4 L45: (Saiz-Lopez and von Glasow, 2012; Wang et al., 2015). -> (e.g. Saiz-Lopez ...).

Re: Corrected.

P4 L46: 'the coldest tropopause' of what? Please specify.

Re: Here we mean that the TWP region has the lowest tropopause temperature over the globe. Corrected as "At the same time, the TWP region has the lowest cold-point tropopause temperature (CPTT) over the globe and plays an important role in controlling the water vapor concentration in the stratosphere."

P4 L49: 'an important region for troposphere-to-stratosphere transport' Please add some references.

Re: Added.

P4 L50: Is the TWP more important for stratospheric chemistry as other regions in the atmosphere? Please clarify?

Re: We thank for the reviewer's comment. Here we want to summarize the importance of the TWP region. The sentence was modified as "The TWP is an important region for tropospheric trace gases being transported from the troposphere to the stratosphere, and therefore influencing the stratospheric

chemistry (e.g., Fueglistaler et al., 2004; Levine et al., 2007; Krüger et al., 2008; Pan et al., 2016) .”

P4 L66-70: The impact of ozone-depleting halogen-containing substances is already mentioned on P3 L42. I propose to combine these two sentences in one paragraph.

Re: These sentences are combined in the first paragraph of Introduction section 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 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).”

P4 L71: 'Based on a trajectory model, Fueglistaler et al. (2004) pointed out that the TWP region is a primary source of the tropospheric air entering the stratosphere and approximately 80% of the trajectories ascending into the stratosphere enter the TTL from the TWP'. However, in L63 it is written: 'the TWP is not the dominant entry of trace gases transported from the troposphere into the lower stratosphere'. Please rephrase this statement more carefully.

Re: Thanks for the comment. The statement is rephrased as: “Though the vertical transport from TTL to the lower stratosphere is dominated by the BD circulation, numerous studies confirmed that the TWP region is an important pathway of the surface air entering the TTL (Fueglistaler et al., 2004; Levine et al., 2007; Krüger et al., 2008; Haines and Esler, 2014). Based on a trajectory model, Fueglistaler et al. (2004) pointed out that approximately 80% of the trajectories ascending into the stratosphere from the TTL are originated from the TWP region.”

P6 L100: 'using reanalysis datasets and model simulations' --> 'using JRA55, ERA5 and MERRA2 reanalysis and different WACCAM4 simulations as described in Sect. 2.'

Re: Corrected.

P6 L102: 'is also discussed.' --> ' will be discussed in Sect. 3'

Re: Corrected.

P6 L110: Please add the horizontal resolution of ERA5 data (0.3° × 0.3°), which is much higher as in JRA55 and MERRA2. What about differences in vertical and temporal resolution. Please specify.

Re: Thanks for the comment. The description of the JRA55, ERA5 and MERRA2 datasets are rephrased in Section 2, and the information about the vertical, horizontal, and temporal resolution are added.

P6 L124: 'UTLS' is not yet introduced in the text.

Re: Corrected.

P6 L125: 'even though there are still large biases in the reanalysis datasets' What are the differences between the three different reanalyses (JRA55, ERA5 and MERRA2) used here? Please specify.

Re: According to the results of Uma et al. (2021), the description is added to the manuscript as: "the updrafts from the JRA55 data in the UTLS are stronger than those from ERA5 and MERRA2 data." It should be mentioned that Uma et al. (2021) did not give quantitative differences between them.

P8 L145: 'except that the global SSTs are fixed to the climatological mean values during 1955-2018 (long-term mean for each calendar month during 1955-2018.' Why are the SST not fixed to a value representative for the beginning of the 60-year period?

Re: The Control and Fixsst simulations are designed to investigate the impact of SST changes on the intensified upward motion over the TWP. For this purpose, using the SST climatology representative for the beginning of the 60-year period to force the simulation should also be proper. Since we compare the trends between the Control (transient) and the Fixsst (constant) simulations, the state of the Fixsst simulation should not influence the results. The SSTs are fixed to the mean of 1958-2017 rather than 1960s to make the mean state of the two simulations more consistent with each other.

P8 L146 Please explain the added-value of a time-slice experiment compared to the hindcast simulation.

Re: Thanks for the comment. The SSTs in the hindcast simulation are prescribed as the observed SSTs, with changes of SSTs over the globe. SSTs in the time-slice simulations are only modified in the eastern maritime continent and the tropical western Pacific (20°S-20°N, 120°E-160°E) , which emphasizes the importance of the SSTs over these areas. The descriptions are clarified in the revised manuscript.

P8 L150: For better motivation, please explain in more detail why this set up is used for the two time-slice simulations.

Re: Thanks for the suggestion. Some explanations are added to the manuscript as: "To figure out the impact of the warming SST over the TWP region on the intensifying trend of the upward motion over the TWP region, a couple of time-slice simulations (R1 and R2) are also integrated for 33 years… Since the

SSTs over the TWP show significantly warming trends, the SSTs during 1998-2017 are higher than the SSTs during 1958-1977. Hence, the difference between R1 and R2 reflect the impact of the warmed SSTs over the TWP on the atmospheric circulation.”

P9 L171: 'the climatological distribution of the vertical velocity at 150 hPa for each month of the year.' --> Mean values of the vertical velocity at 150 hPa for each month averaged over 60 years from 1958 to 2017. Yes?

Re: Yes. The statement is corrected correspondingly.

Why is JRA55 and not ERA5 or MERRA2 selceted for Fig.1? What are the difference between JRA55 and ERA5/MERRA2?

Re: The pattern of the 150 hPa vertical velocity from JRA55 data shown in Fig. 1 is similar to the patterns of the 150 hPa vertical velocity from ERA5 and MERRA2 datasets. To avoid repetition, only the result from JRA55 data is shown in Fig. 1. According to the referee’s comment, the climatological mean vertical velocity in NDJFM in ERA5 and MERRA2 is added to the supplementary material. The vertical velocity differences between JRA55 and the ERA5 and MEERA2 data are further discussed in the revised manuscript.

P9 L180: please add text within ++: 'which is more important to the transport of air over the TWP from the lower troposphere to the TTL +compared to the summer months (as shown in Fig. 1) + and subsequently to the lower stratosphere.

Re: Corrected.

P9 L182: 'Notably, the 150 hPa w shows no subsidence over the maritime continent, while there is descending motion over the maritime continent at 100 hPa (not shown), which is referred to the “stratospheric drain” (Gettleman et al., 2000; Sherwood, 2000).' The 100 hPa values should be shown in an electronic supplement.

Re: The 100 hPa *w* values using JRA55, ERA5 and MERRA2 are shown in Supplementary Fig. 2.

P10 L186: Please explain in detail how the trend is calculated.

Re: We thank for the reviewer's suggestion. The description about the trend and the significance test is added to Section 2 as:

"Linear trends and the significance test. 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:** $\sigma = b\sqrt{\frac{\frac{1}{r^2}-1}{n-2}}$ **."**

P10 L187: 'using reanalysis datasets' -> 'using JARA55, ERA5 and MERRA2 reanalyses.'

Re: Corrected.

P10 L191: ->'is intensifying through the troposphere from 1958 to 2017.'

Re: Corrected.

P10 L193 : add 'used here' or 'used in this study'

Re: Added.

Figure 2: In MERRA2 the horizontal winds seems to be much stronger compared to JARA55 and ERA5. Could you make a comment on this. Please discuss the similarities and differences of the three reanalyses in more detail. Maybe you could show an additional figure showing the differences of ERA5 and MERRA2 compared to JARA55. ERA5 has much higher spacial and temporal resolution as JRA55 and MERRA2, therefore I would expect pronounced differences to JARA55 and MERRA2, in particular convection is much improved compared to the previous ECMWF reanalysis ERA-Interim.

Re: Thanks for the comment. In Fig. 2, the trends of the horizontal winds seem to be much stronger in MERRA2 compared to JRA55 and ERA5. It should be noted that the wind trends in JRA55 and ERA5 are calculated during the period 1958-2017, however, the wind trends of in MERRA2 are calculated during the period 1980-2017. To further figure out whether there are large differences between the trends of the winds between JRA55, ERA5 and MERRA2, the trends of winds during 1980-2017 in NDJFM derived from JRA55, ERA5 and MERRA2 are shown here (and in the supplementary material). It could be seen that the trends of horizontal winds in Figs. R3a and R3b are larger than the trends of horizontal winds in Figs. 2a and 2b (in manuscript). And there are insignificant differences between the trends of horizontal winds in JRA55, ERA5, and MERRA2. Hence, the differences of the trends of the horizontal winds in Fig. 2 are mainly due to the different time periods which are used to calculate the trends. The trend patterns of the winds in JRA55, ERA5, and MERRA2 are similar. However, there are also some differences between the trends of vertical velocity in JRA55, ERA5, and MERRA2. There are significantly positive trends over the TWP regions in JRA55, ERA5, and MERRA2, while the positive trends of vertical velocity over the TWP in ERA5 seem to be weaker than those in JRA55 and MERRA2. Comparing to the negative trends of the vertical velocity

over the central Pacific in JRA55 and ERA5, the negative trends of the vertical velocity over the central Pacific in MERRA2 extend more northward. The above discussion is added to the corresponding paragraph in the revised manuscript.

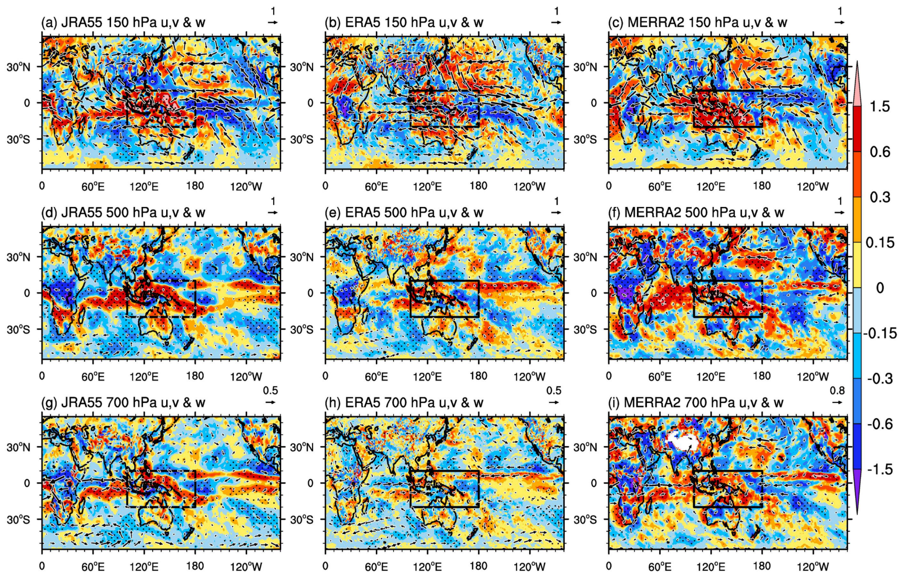

Fig. R3. The trends of the vertical velocity and horizontal winds in NDJFM using JRA55 (a, d, g), ERA5(b, e, h) and MERRA2(c, f, i) data during 1980-2017 at different levels. (a)-(c) are the trends of winds at 150 hPa. (d)-(f) are the trends of winds at 500 hPa. (g)-(i) are the trends of winds at 700 hPa. The trends of vertical velocity over the dotted region are statistically significant at the 90% confidence level.

Figure 3: Please Explain how 'standardized intensity' is calculated. What is the reason for the extreme minima (1981, 1991, 1999)? El Niño Southern Oscillation (ENSO)?

Re: "The intensity of the upward motion over the TWP is simply defined as the area-averaged upward mass flux at a specific level. And the standardized intensity is the intensity divided by the standard deviation of the intensity at the corresponding level." The explanation of the standardized intensity is added to

the manuscript. The extreme minima (actually, the years are 1982, 1991, and 1997) are mainly due to the ENSO events (El Niño), which may result in a weak upward motion over the TWP (e.g., Levine et al., 2008; Hosking et al., 2012; Hu et al., 2016). To figure out the influence of the El Niño events (1982, 1991, 1997), the time series of the standardized intensity of the upward motion over the TWP in NDJFM after removing the ENSO signal using the linear regression method (Hu et al., 2018) in JRA55, ERA5, and MERRA2 are shown here (Fig. R4 and Supplementary Fig. 5). 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). Notably, the upward motions over the TWP at 150 hPa, 500 hPa, and 700 hPa in NDJFM in JRA55, ERA5, and MERRA2 still show statistically significant intensifying trends after removing the ENSO signal in Supplementary Fig. 5, which suggests that ENSO events exert limited impacts on the trends of the upward motion over the TWP in NDJFM during 1958-2017. Some of above discussions are added to the revised manuscript.**

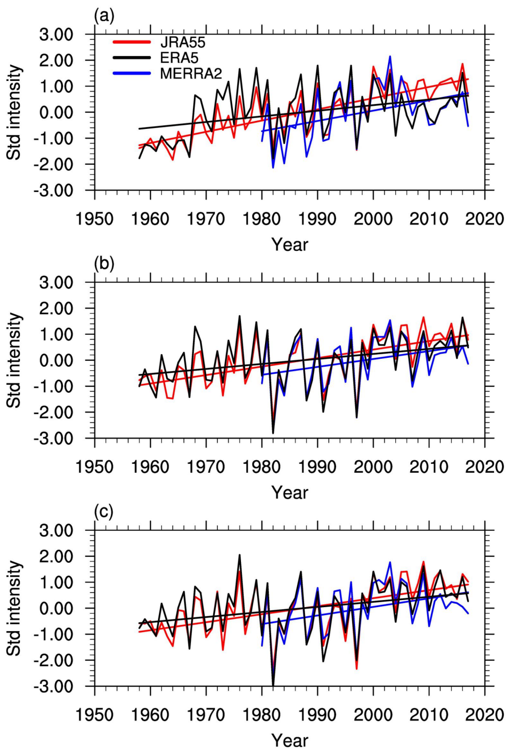

Fig. R4. The time series of the standardized intensity of the upward motion over the tropical western Pacific (20°S-10°N, 100°E-180°E) at (a) 150 hPa; (b) 500 hPa; and (c) 700 hPa extracted from JRA55 (red), ERA5 (black) and MERRA2 (blue) datasets after removing the ENSO signal using linear regression 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.

P10 L201: 'This suggests a comprehensive enhancement of vertical velocity though the whole troposphere, which is evident from the surface to 100 hPa (not shown).' Figures demonstrating this could be shown in an electronic supplement.

Re: The trends of vertical velocity from the surface to 100 hPa in NDJFM derived from JRA55, ERA5, and MERRA2 are added in the supplementary material (Supplementary Fig. 4)

P10 L205 :'Due to the data limitation, it is not possible to show the corresponding changes of trace gases by observations.' I agree that it is difficult to find observation from 1958 to 2017. However satellite measurements from shorter time period could be used (e.g. MLS CO available since August 2004; https://mls.jpl.nasa.gov).

Re: We thank for the referee’s comment. An extra figure showing the trends of CO observed by MOPITT and MLS at around 200 hPa during 2000-2017 and 2005-2017 is added in the revised manuscript. The details could be found in the responses to the major comments above.

P11 L210: 'of observed OLR' --> 'of observed OLR provided by NOAA (see Sect. 2)'

Re: Corrected.

P11 L222: 'CPTT' is not yet introduced. Fig. 4b is not referred to in the text --> '.. the cold-point tropopause temperature (CPTT; see Fig. 4b) shows significantly decreasing trends over the TWP in NDJFM during 1958-2017,... However negative trends are also found in other regions in low and mid-altitudes, except in the Pacific.'

Re: CPTT is introduced in the revised manuscript *Line 55*. The statement is corrected.

P12 L242: 'The SSTs over the TWP are positively correlated with the upward motion intensity over the TWP, while the SSTs over tropical central, eastern Pacific, and Indian Ocean show negative correlations.' I am wondering that the positive correlation pattern is somewhat shifted to the east, then the western part of the maritime continent (100°E-120°E) is also negative correlated. However, in the western part of the maritime continent (100°E-120°E) the trends of horizontal winds (Fig. 2) are large. Maybe, it is useful to avoid misunderstandings to mark the region of the TWP somehow (e.g. by a box).

Re: We are sorry for the possible confusion. The TWP is marked by a box in the figures of the revised manuscript, and the corresponding statement is corrected to avoid the confusion.

P13 L253: 'a couple of model simulations' --> 'a couple of model simulations with WACCAM4'

Re: Corrected.

P14 L277: 'a couple of time-slice runs (R1 and R2) are performed (more details are given in the section 2).' --> It is maybe a matter of taste, but I would prefer in general to say 'simulations instead of 'run'. Please repeat the main features of R1 and R2 as a reminder for the reader.

Re: Corrected. And the main features of R1 and R2 are added to the corresponding paragraph.

P14 L289: 'The changes in the OLR' --> 'The changes in the OLR simulated in WACCAM4'

Re: Corrected.

P15 L300: 'We now discuss about the relationship between the trends of the upward motion over the TWP and the changes of the trace gases in the lower stratosphere.' -->'The relationship between the trends of the upward motion over the TWP and the change of CO and water vapor in the lower stratosphere simulated with WACCAM4 will be analyzed. It is expected, that a positive trend in the upward motion over the TWP yield higher CO in the lower stratosphere caused be enhanced vertical upward transport. However, water vapor mixing ratios in the lower stratosphere depends in addition from the temperature in the UTLS ....' Is that what you would like to discuss here?

Re: Yes. The corresponding phrases are corrected.

Section 3.3 is written somewhat confusing, therefore I propose to write a short introduction of Sect. 3.3 summarizing previous results from the literature and subsequent the new results of Qie et al.

Re: Thanks for the comment. A short introduction of Section 3.3 is added to the manuscript according to the comments of the referee and the literature.

“Previous studies showed that the enhanced deep convection and upward motion could lead to increased CO in the UTLS (e.g., Duncan et al., 2007; Livesey et al., 2013). At the same time, water vapor mixing ratios in the UTLS may increase due to the enhanced upward motion which could bring more wet air from low altitude to high altitude (e.g., Rosenlof, 2003; Lu et al., 2020). However, the water

vapor mixing ratios in the lower stratosphere also depend on the tropopause temperature (e.g., Highwood and Hoskins, 1998; Garfinkel et al., 2018; Pan et al., 2019). Hence, the relationship between the intensity of upward motion and the water vapor concentration in the UTLS is complex. Here, the relationship between the trends of the upward motion over the TWP and the changes in CO and water vapor in the ULTS simulated with WACCM4 are analyzed.”

P15 L303: 'in different simulations are displayed' --> 'are shown based on the Control and the Fixsst simulation as well as using their difference..'

Re: Corrected.

P15 L303: --> 'in Fig. 7d-i'

Re: Corrected.

P16 L328: 'As mentioned above in section 3.1, the observed tracer gases (e.g., CO) have very limited data record and may be affected by a mixture of anthropogenic and natural (e.g., biomass burning) emissions and the ENSO events (e.g., Duncan et al., 2007; Logan et al., 2008). It is therefore very hard to identify the relative contribution of single factors.' This sentence is here not very helpful, please remove it.

Re: Removed.

P16 L332: 'We utilize the numeric simulations' --> 'We use the Control and the Fixsst simulation with WACCAM4 ..'

Re: Corrected.

P17 L344: 'increasing trends over the TWP' How much is the increase in CO within 60 years? Please add some numbers in the text. (4*10^{-4} ppm per year -> 0.024 ppm change in CO in 60 years; that seems not to be much.)

Give some reference about CO values and variability of CO in this region from measurements to assess the trend in CO over TWP.

Re: Thanks for the suggestion. We show the climatological mean CO values at 215 hPa in NDJFM from MLS observations during 2005-2017 and at 200 hPa in NDJFM from MOPITT observations during 2000-2017. The concentration of MLS CO over the TWP is approximately 80 ppbv at 215 hPa and MOPITT CO is 70 ppbv at 200 hPa, which is consistent with previous study (e.g., Huang et al., 2016). The increasing trends of CO at 150 hPa over the TWP in the Control and Fixsst simulations are approximately 3.4 ppbv decade^{-1} (20.4 ppbv within 60 years) and 3.2 ppbv decade^{-1} (19.2 ppbv within 60 years). The CO at 150 hPa over the TWP derived from the difference between the Control and Fixsst increased 0.2 ppbv decade^{-1} (1.2 ppbv within 60 years), which suggests that the enhanced deep convection and intensified upward motion could lead to an extra 6% increasing trend of CO at 150 hPa over the TWP. It should be mentioned that the changes in the CO at 150 hPa caused by the intensified upward motion over the TWP not only depend on the vertical transport but also on the gradient of CO concentration at around 150 hPa (Garfinkel et al., 2013). This may be the reason why the intensifying upward motion over the TWP only contribute to an extra 6% increasing trend of CO at 150 hPa in NDJFM during 1958-2017. For example, CO derived from the difference between the Control and Fixsst simulations shows higher increasing trends in the layer 150-70 hPa (0.4 ppbv decade^{-1}) than those at 150 hPa (0.2 ppbv decade^{-1}), which is due to the greater CO gradient in the UTLS comparing to the CO gradient in the upper troposphere.

P17 L354: 'This is consistent with our results which show intensified northerlies over the subtropical Indian Ocean and strengthened westerlies over the subtropical Indian Ocean and western Pacific'

Please add some numbers in the text: how much is the strengthening. Is it a large or weak change. Please give the reader some numbers to assess this change.

Re: Thanks for the suggestion. The trends of the northerlies over the subtropical Indian Ocean (15°S-25°S, 60°E-100°E) are approximately 0.2 m s^{-1} $decade^{-1}$ and the trends of westerlies over the subtropical Indian Ocean and western Pacific (20°N-35°N, 60°E-160°E) are approximately 0.3 m s^{-1} $decade^{-1}$ (Figs. 5c and f). The discussion is added to the revised manuscript.

P18 L377: 'In summary, the increase of CO as shown in Figs. 8a-8b is mainly caused by surface emissions.' My understanding is that the surface emissions are the same in the Control and Fixsst simulation and that the increase of UTLS CO is caused by stronger upwelling. Please clarify.

Re: We are sorry for the confusion. The surface emissions are the same in the Control and Fixsst simulations, which are increasing in NDJFM during 1958-2017. Hence, the trends of CO in Fig. 9a (in the revised manuscript) contain the CO trends induced both by the increased surface emissions and the enhanced upward motion. The trends of CO over the TWP in Fig. 9b (in the revised manuscript) only include the CO trends induced by the increased surface emissions since the upward motion over the TWP in the Fixsst simulation shows weak trends. Furthermore, the CO increased through the troposphere over the TWP using the difference between the Control and Fixsst simulations, which suggests that the increase of CO in the upper troposphere in Fig. 9c (in the revised manuscript) is caused by the intensified upward motion over the TWP. Some discussions are added to the text.

Figure 11: '(a) Control run; (b) Fixsst run; (c) difference between the Control run and the Fixsst run; and (d) JRA55.' --> labels a,b,c,d are not consistent to Fig.11.

Re: We are sorry for the mistake. The figure caption is corrected.

Why is MERRA2 and ERA5 not shown. How is the trend of the BD circulation calculated? Are zonal mean values shown? Please clarify.

Re: Thanks for the suggestion. We have added the trends of the BDC derived from ERA5 and MERRA2 to the supplementary material. The trend of the BDC is calculated using the simple least square regression. The $w*$ used in the manuscript is calculated using the TEM formula and $w*$ denotes the monthly zonal mean of the vertical component of the BDC. To avoid confusion, the $\overline{w}^*$ and $\overline{v}^*$ in the equation mentioned in the original manuscript are corrected as w^* and v^* in the revised manuscript.

P19 L384: 'The tropical upwelling of BDC (w*) are significantly increased in the lower stratosphere over past decades as seen in both reanalysis data and the control run (Figs. 11a and b).' --> 'in JARA55 and control simulation'

Re: Corrected.

Please indicate that the TEM is used to calculate w*. Please specify 'significantly increased' with some numbers. Please compare the increase with numbers from other references.

Re: We thank the referee's comment. The manuscript is revised correspondingly. The quantitative results and the comparison with other references are added.

The tropical upwelling of BDC (w^*) 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±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 with a rate of 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 at a rate of 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 the previous studies. Overall, the trends of the tropical upwelling of BDC using JRA55, MERRA2 data and the Control simulation are similar to the 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 using 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 BD circulation 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 contribute to the transport of the tropospheric trace gases from the TTL to a higher level. The increased concentration of CO in the UTLS in Fig. 9c 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.

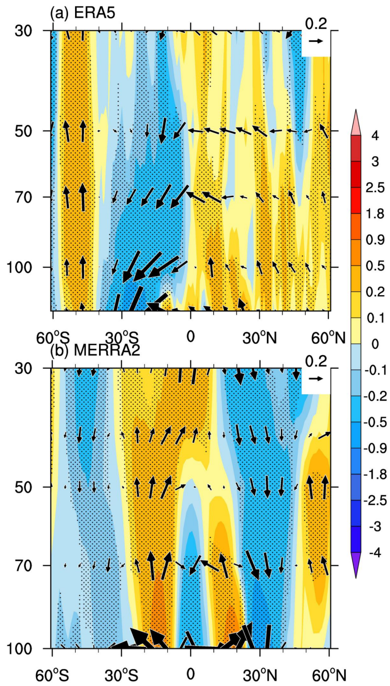

Fig. R5. The trends of the BD circulation (vectors) calculated using the TEM formula using ERA5 and MERRA2 data. (a) The trends of w* (10^{-5} m s^{-1} a^{-1}) and v* (10^{-2} m s^{-1} a^{-1}) in NDJFM during 1958-2017 using ERA5 data. (b) The trends of w* (10^{-5} m s^{-1} a^{-1}) and v* (10^{-2} m s^{-1} a^{-1}) in NDJFM during 1980-2017 using MERRA2 data. The shadings are the trends of the vertical velocities (10^{-5} m s^{-1} a^{-1}). The trends of the vertical velocity over the dotted regions are statistically significant at the 90% confidence level.

P19 L400: 'The recent trends of the upward motion from the lower to the upper troposphere in boreal winter over the TWP is investigated for the first time based on the reanalysis datasets and model simulations.' Specify which reanalysis and which model runs are used.

Re: Corrected.

P19 L405: 'Warmer SSTs over the TWP lead to a strengthened Pacific Walker circulation, enhanced deep convection and stronger upward motion over the TWP.' Please make this statement more quantitative. From the analysis it is not clear for me what is enhanced: convection or subsequent upward motion over the TWP by diabatic heating or both.

Re: Thanks for the suggestion. The statement is rephrased. Both of the deep convection and the subsequent upward motion over the TWP by diabatic heating are enhanced. We are sorry for the confusion.

How is downward transport over TWP by the Pacific Walker circulation during El Niño considered within the analysis? Please clarify?

Re: Thanks for the comment. The impact of ENSO events on the upward motion over the TWP is discussed in the revised manuscript according to the referee's suggestion. Some discussions are also added in the Summary and Discussion.

P20 L410:' Model simulations indicate that the CO concentration increases significantly from the surface to the stratosphere with increased surface emissions.' Please make the statement more quantitative.

Re: Thanks for the comment. The statement is rephrased as: "Results from the Control simulation indicate that the CO concentration increased significantly from the surface to the stratosphere over the TWP. The CO at 150 hPa increased at a rate of approximately 3.4 ppbv decade^{-1} with increased surface emissions and the enhanced upward motion over the TWP. Specifically, an enhancement of tropospheric upward motion and subsequent upward transport of trace gases over the TWP lead to an extra 6% increasing trend of CO concentrations in the upper troposphere. Furthermore, the upward mass fluxes at 70 hPa in the tropics (15°S-15°N) show strengthening trends at rates of 2.8±1.9% decade^{-1} and 4.6±4.3% decade^{-1} in JRA55 data (during 1958-2017) and MERRA2 data (during

1980-2017), respectively, which is consistent with previous studies (e.g., Butchart et al., 2010; Fu et al., 2019; Rao et al., 2019).”

P20 L417: 'Trace gases and aerosols in the stratosphere have important impacts on the stratospheric processes, and hence influence the troposphere weather and climate through their radiative and dynamical feedback'. This statement is very general. Please be more specific here.

Re: We thank the referee’s comment. The statement is rephrased as: “Trace gases and aerosols entering the stratosphere from the troposphere have important impacts on the stratospheric processes. For example, ozone-depleting substances, CH_4 and N_2O could influence on the stratospheric ozone significantly (e.g., Shindell et al., 2013; Wang et al., 2014; WMO, 2018), which also modify the temperature in the stratosphere significantly through their strong radiative effects. Water vapor in the lower stratosphere, in particular, has a significant warming effect on the surface climate (Solomon et al., 2010). Therefore, changes of trace gases in the UTLS have important impacts on both tropospheric and stratospheric climate.”

My impression is that the conclusion section should be revised to summarize the results of Qie et al in a much more quantitative way.

Re: Thanks for the referee’s suggestion. The conclusion section is revised according to the quantitative results in the revised manuscript.

The conclusion section is rewritten as:

“The recent trends of the upward motion from the lower to the upper troposphere in boreal winter over the TWP is investigated for the first time based on the JRA55, ERA5, MERRA2 datasets and four WACCM4 simulations (more details could be found in Section 2). The upward motion at 150 hPa over the TWP in NDJFM increased 8±3.1% decade^{-1} and 3.6±3.3% decade^{-1} in NDJFM from 1958 to 2017 in JRA55 and ERA5 reanalysis datasets, respectively. Despite

the possible discontinuities between the radiosonde era (after 1958) and the satellite era (after 1979), the upward motion at 150 hPa over the TWP in NDJFM increased 7.5±7.1% decade^{-1} during 1980-2017 in MERRA2 data. Such intensification of the upward motion over the TWP also exist in the middle- and lower-troposphere in NDJFM in JRA55, ERA5, and MERRA2, which can be confirmed by the WACCM4 model simulations. Comparing the results between the Control and Fixsst simulations with WACCM4, it is found that the trend of the upward motion over the TWP is closely related to the changes in global SSTs, especially the SST warming over the eastern maritime continent and tropical western Pacific (see the results from the experiments R1 and R2 in Fig. 7). Warmer SSTs over the eastern maritime continent and tropical western Pacific (approximately 0.5 K) lead to a strengthened Pacific Walker circulation, enhanced deep convection and approximately 27% intensified upward motion at 150 hPa over the TWP as shown by the results from the experiments R1 and R2. The enhanced deep convection over the TWP could lead to a dryer lower stratosphere over the TWP, as the strong upward motion and the Rossby-Kelvin wave responses induce a colder tropopause over the TWP. It should be pointed out that the results in the present study are mainly based on the reanalyses data, and some uncertainties may exist. More observational data are expected to be used to obtain a more robust result in the future.

Results from the Control simulation indicate that the CO concentrations increased significantly from the surface to the stratosphere over the TWP. The CO at 150 hPa increased at a rate of approximately 3.4 ppbv decade^{-1} with increased surface emissions and the enhanced upward motion over the TWP. Specifically, an enhancement of tropospheric upward motion and subsequent upward transport of trace gases over the TWP lead to an extra 6% increasing trend of CO concentrations in the upper troposphere.

Furthermore, the upward mass fluxes at 70 hPa in the tropics (15°S-15°N) show strengthening trends at rates of 2.8±1.9% decade^{-1} and 4.6±4.3% decade^{-1} using JRA55 data (during 1958-2017) and MERRA2 data (during 1980-2017) in

NDJFM, which is consistent with previous studies (e.g., Butchart et al., 2010; Fu et al., 2019; Rao et al., 2019). However, such enhancement in tropical upward mass flux at 70 hPa has large uncertainties since the ERA5 data show a negative and insignificant trend (Supplementary Fig. 7a). The results from the Control and Fixsst simulations indicate that the elevated CO in the upper troposphere is further uplifted to the lower stratosphere by the intensified tropical upwelling of the BD circulation due mainly to global SST warming and lead to an increase of CO in the lower stratosphere. An extra 14% increasing trend of CO at the layer 150-70 hPa over the TWP is derived from the Control and Fixsst simulations..."

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