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Enhanced upward motion through the troposphere over the tropical western Pacific and its implication to transport of trace gases from the troposphere to the stratosphere

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Abstract

The tropical western Pacific (TWP) is a preferential area of air uplifting from the surface to the upper troposphere. 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 from 1958 to 2017 using the reanalysis datasets. Model simulations using the Whole Atmosphere Community Climate Model, version 4 (WACCM4) suggest that warming global sea surface temperatures (SSTs), particularly TWP SSTs, play a dominant role in the intensification of the upward motion by strengthening the Pacific Walker circulation and enhancing the deep convection over the TWP. Using CO as a tropospheric tracer, numeric simulations show that more CO could be elevated to the tropical tropopause layer (TTL) by the enhanced upward motion over the TWP and subsequently into the stratosphere by the strengthened Brewer-Dobson (BD) circulation which is also mainly caused by global SST warming. This implies that more tropospheric trace gases and aerosols may enter the stratosphere through the TWP region and affect the stratospheric chemistry and climate.

Keywords: Troposphere-to-stratosphere transport; Tropical western Pacific; Trend; Sea surface temperature

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1 Introduction

The tropical western Pacific (TWP) is a critical region for tropical and global climate (e.g., Webster et al., 1996; Hu et al., 2020). It has the largest area of warm sea surface temperature (exceeding 28 ^{o}C) which fuels intense and massive deep convection and thus is the largest source of latent heat and water vapor into the atmosphere (Webster and Lukas, 1992). The TWP region is also the most important source of tropospheric air entering the stratosphere due to the strong upward motion and deep convection over this region (e.g., Fueglistaler et al., 2004; Pan et al., 2016). Through the TWP region, tropospheric trace gases, e.g., the organic halogen species, are elevated from the surface to the upper troposphere and lower stratosphere, which affects the ozone concentration and other chemical processes in the stratosphere (Saiz-Lopez and von Glasow, 2012; Wang et al., 2015). At the same time, the TWP region has the coldest tropopause and plays an important role in controlling the water vapor concentration in the stratosphere (e.g., Fueglistaler et al., 2009; Newell and Gould-Steward, 1981; Pan et al., 2016; Randel and Jensen, 2013). Hence, the TWP is also an important region for troposphere-to-stratosphere transport and stratospheric chemistry.

The TWP was thought to be the main pathway of the troposphere-to-stratosphere transport. A concept of "stratospheric fountain" was proposed by Newell and Gould-Steward (1981), which suggested that the poor-water vapor air in the stratosphere stems mainly from the TWP region. However, following studies using the

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observational and reanalysis data showed that there is subsidence at the near-tropopause level over the maritime continent, which is named as the "stratospheric drain" (Gettelman et al., 2000; Sherwood, 2000; Fueglistaler et al., 2004). Further studies verified that the large-scale transport from the tropical tropopause layer (TTL) to the stratosphere is dominated by the upward branch of the Brewer-Dobson (BD) circulation (Brewer, 1949; Dobson, 1956; Holton et al., 1995) while the local upwelling may play a minor role (e.g., Levine et al., 2007; Fueglistaler et al., 2009; Schoeberl et al., 2018).

Though the TWP is not the dominant entry of trace gases transported from the troposphere into the lower stratosphere, 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). The very short lived substances, which play an important role in regulating the ozone concentration, could be elevated to the TTL by the strong upward motion and the deep convection over the TWP and subsequently into the stratosphere by the large-scale upwelling (e.g., Levine et al., 2007, 2008; Navarro et al., 2015). 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. Bergman et al. (2012) suggested that the tropospheric air over the TWP enters the stratosphere mainly in boreal winter, while less air over the TWP could be transported into the stratosphere during boreal summer. Other studies also found that the TWP region is an important

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source of the tropospheric trace gases in the TTL (e.g., Newton et al., 2018; Pan et al., 2016; Wales et al., 2018), even the polluted air from East Asia could be transported rapidly to Southeast Asia by meridional winds and subsequently be elevated to the tropical upper troposphere by the strong upward motion and the deep convection (Ashfold et al., 2015). Hence, the strength of the upward motion over the TWP region during boreal winter is a key feature for understanding the variations of trace gases in the TTL and therefore important for stratospheric chemistry and climate.

The strength of the TWP upward motion is closely related to atmospheric circulation and deep convection. The ascending branch of the Pacific Walker circulation and the strong deep convection over the TWP allow rapid transport from the surface to the upper troposphere (Hosking et al., 2012). In association with global warming, atmospheric circulation, deep convection as well as the boundary conditions (e.g., sea surface temperature; SST) have been changed. For example, the Hadley cell has been extended to the subtropics and the Walker circulation over the Pacific has been shifted westward over the past decades (e.g., Lu et al., 2007; Garfinkel et al., 2015; Ma and Zhou, 2016). At the same time, SSTs over most of areas are getting warmer (Cane et al., 1997; Deser et al., 2010), which modulates the deep convection and atmospheric wave activities in the troposphere and then lead to changes of atmospheric circulations from the troposphere and the stratosphere (e.g., Garfinkel et al., 2013; Xie et al., 2012, 2014a; Wang et al., 2015; Hu et al., 2016; Lu et al., 2020). However, how the strength of the upward motion in the lower TTL over the TWP region has been changed over the past decades remains unclear. In this study, we

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investigate the long-term trend of the upward motion over the TWP using reanalysis datasets and model simulations. The implication of the changes in the upward motion over the TWP to the transport of trace gases from the surface to the upper troposphere and lower stratosphere is also discussed.

2 Data and method

Reanalysis data. Three reanalysis datasets, including JRA55, ERA5 and MERRA2 are used in this study. The Japanese 55-year Reanalysis (JRA55) is conducted by the Japan Meteorological Agency (JMA). JRA55 is produced by an atmospheric model with higher spatial resolution (T319L60), using a four dimensional variational (4D-Var) data assimilation system. It has a horizontal resolution of 1.25°×1.25°, and covers the period from 1958 to present (Kobayashi et al., 2015; Harada et al. 2016). The ERA5 reanalysis is the newest generation product from the European Centre for Medium Range Weather Forecasting (Hersbach et al., 2020). The ERA5 data also extend back to 1958, which is coinciding with the time that radiosonde observations in the Arctic became more systematic and regular. It should be noted that the ERA5 data suffers from a bias during 2000-2006, and is replaced by the ERA5.1 data in this period here. The Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA2; 1.25°×1.25° horizontal mesh) dataset are also used, which is only accessible after 1980 (Gelaro et al., 2017). The monthly mean air temperature, horizontal wind fields and vertical velocity at different pressure levels are extracted from the three Reanalysis data sets. The accuracy of the vertical velocity in reanalysis data sets has been evaluated by the

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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 (Uma et al. 2021). 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. Hence, the present study investigate the long-term trend of the upward motion over the TWP from 1958 to 2017.

SST and OLR data. The SST data is from the HadISST dataset (1°×1° horizontal mesh) during 1958-2018 (Rayner et al., 2003). The outgoing longwave radiation (OLR), which is utilized to reflect the deep convection in the tropics, is extracted from NOAA Interpolated OLR dataset on a 2.5°×2.5° horizontal mesh during 1974/11-2018/03 (Liebmann and Smith, 1996).

Model simulations. A series of the Whole Atmosphere Community Climate Model version 4 (WACCM4) simulations are performed to find out the main impact factors of the trend of the upward motion over the TWP. The WACCM4 used in this study is an atmosphere-only model with a horizontal resolution of 1.9°×2.5°, which has a vertical resolution of 66 vertical levels (Marsh et al., 2013). A hindcast simulation (Control run) is performed with observed greenhouse gases, solar irradiances, and prescribed SSTs (HadISST dataset is used) during 1955-2018. A

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single-factor controlling run (Fixsst run) is done for the same period with the same forcings, 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). A couple of time-slice simulations are also integrated for 33 years to investigate the impact of the SST over the TWP region on the trend of the upward motion over the TWP. The SSTs of both simulations are prescribed as the climatological mean SST during 1958-2017, while the SST anomalies over the tropical western Pacific (20°S-20°N, 120°E-160°E) in the boreal wintertime (November to March of the next year, NDJFM) during 1998-2017 are added to one (R1) simulation and SST anomalies over the tropical western Pacific (20°S-20°N, 120°E-160°E) in NDJFM during 1958-1977 are added to the other simulation (R2). The first 3 years of the numeric simulations are not used in the present study to provide a spin-up.

Transformed Eulerian Mean (TEM) Calculation. To diagnose the changes in the BD circulation, the meridional and vertical velocities of the BD circulation are calculated by the TEM equations (Andrews and Mcintyre, 1976):

$$\overline{v}^{*} = \overline{v} - \frac{1}{\rho}\left(\frac{\rho \overline{v'\theta'}}{\overline{\theta}_z}\right)_z$$

$$\overline{w}^{*} = \overline{w} + \frac{1}{a\cos\varphi}\left(\cos\varphi \frac{\overline{v'\theta'}}{\overline{\theta}_z}\right)_\varphi$$

Where $\overline{v}^{*}$ and $\overline{w}^{*}$ denote the meridional and vertical velocities of the BD circulation; the overbar represents the zonal mean; the prime denotes the deviation from the zonal mean; θ, a, φ, and ρ indicate the potential temperature, the radius of the earth, the latitude, and the standard density.

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3 Results

3.1 Enhanced upward motion over the TWP

According to previous studies, the lapse-rate tropopause is a good proxy to separate the tropospheric and the stratospheric dynamic behavior (vertical motion dominated and horizontal mixing dominated, respectively) over the TWP (Pan et al., 2019). Since the lapse-rate tropopause over the TWP in the boreal winter is near 100 hPa (not shown), we utilize the vertical velocity at 150 hPa to reflect the vertical transport in the upper troposphere. Figure 1 shows the climatological distribution of the vertical velocity at 150 hPa for each month of the year. The TWP region at the UTLS level has strong upward motion due to the frequent intense deep convection and the Pacific Walker circulation. It is noteworthy that there is strong upward motion at 150 hPa in NDJFM over the TWP, while the upward motion in other months shifts northward corresponding to the Asia summer monsoon. This is consistent with previous studies (Newell and Gould-Steward, 1981; Bergman et al., 2012). Therefore, we mainly focus on the changes in the upward motion in NDJFM, which is more important to the transport of air over the TWP from the lower troposphere to the TTL and subsequently to the lower stratosphere. The 150 hPa vertical velocity (w) shows positive values over the TWP, which are almost symmetry along the equator in NDJFM (Fig. 1). 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).

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Figure 2 displays the linear trends of *w* in the upper (150 hPa), middle (500 hPa) and lower (700 hPa) troposphere in NDJFM from 1958 to 2017 using three reanalysis datasets. The 150 hPa *w* increased significantly over the TWP during 1958-2017 (Fig. 2). Additionally, the upward motion over the TWP in the lower and middle troposphere also shows significantly intensifying trends (Figs. 2b and c). This indicates that the upward motion over the TWP is intensifying through the troposphere. Such an enhancement of the upward motion over the TWP is evident in all three reanalysis datasets (JRA55, ERA5, and MERRA2).

The time series of the upward motion intensity over the TWP (vertical velocity averaged for the region 20°S-10°N, 100°E-180°E) from different datasets are given in Fig. 3. The intensity of the upward motion over the TWP at 150 hPa increases significantly in NDJFM during last decades, which can be confirmed by all the three reanalysis data (Fig. 3). The intensity of the upward motion over the TWP in the lower and middle troposphere is also enhanced significantly (Figs. 3b and c). This suggests a comprehensive enhancement of vertical velocity though the whole troposphere, which is evident from the surface to 100 hPa (not shown). While the trace gases in the TTL are modulated by the upward motion and subsequent vertical tranport (e.g., Garfinkal et al., 2013; Xie et al., 2014b), such a strengthening of the upward motion over the TWP may lead to the more tropospheric trace gases in the TTL. Due to the data limitation, it is not possible to show the corresponding changes of trace gases by observations. However, we will discuss the CO changes by model simulations in section 3.3.

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The changes in the atmospheric circulation at the UTLS level in the tropics are closely related to the changes in the tropical deep convection and SSTs (e.g., Levine et al., 2008; Garfinkal et al., 2013; Xie et al., 2020). Here, the trends of observed OLR in NDJFM during 1974-2017 are shown in Fig. 4a. Though the time period of the observed OLR data is shorter than the time period we analyzed, the changes in OLR could partly reflect the changes in the deep convection during 1958-2017. The OLR shows significantly negative trends over the TWP which indicates intensified deep convection over the TWP. The OLR trend pattern is very similar to the trend pattern of the 150 hPa *w* (Figs. 2a-c), which indicates that the increasing trends of 150 hPa *w* are closely related to the intensified deep convection over the TWP. The intensified deep convection not only lead to the strengthened upward motion in the UTLS (Highwood and Hoskins, 1998; Ryu and Lee, 2010), but also result in the decreased temperature near the tropopause which plays a dominant role in modulating the lower stratospheric water vapor concentration (e.g., Hu et al., 2016; Wang et al., 2016). Corresponding to the enhanced deep convection over the TWP, the CPTT shows significantly decreasing trends over the TWP in NDJFM during 1958-2017, which is consistent with Xie et al., (2014a).

The changes in the deep convection over the tropical Pacific may be related to the changes in the Pacific Walker circulation. The Pacific Walker circulation shows a significant intensification over the past decades (e.g., Meng et al., 2012; L'Heureux et al., 2013; McGregor et al., 2014). The vertical velocity at 500 hPa and 150 hPa shows significantly positive trends over the TWP in NDJFM during 1958-2017 (Fig. 2).

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Meanwhile, the lower tropospheric zonal wind shows easterly trends over the tropical Pacific, while the upper tropospheric zonal wind shows westerly trends over the tropical Pacific, which suggests a strengthened Pacific Walker circulation and is consistent with previous studies (Hu et al., 2016; Ma and Zhou, 2016).

The strengthened Pacific Walker circulation is closely related to the changes in the SSTs (e.g., Meng et al., 2012; Ma and Zhou, 2016). The trends of the SSTs in NDJFM during 1958-2017 are shown in Fig. 4c. The SST shows significantly warming trends almost over the world except the central Pacific in NDJFM during 1958-2017. In addition, the intensity of the upward motion over the TWP is significantly correlated with the SST (Fig. 4d), which suggests that the SST has important effects on the upward motion over the TWP. The correlation coefficient in Figure 4d shows a La Niña-like pattern and indicates that the ENSO events exert important impacts on the upward motion over the TWP (Levine et al., 2008). 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 with the intensity of the upward motion over the TWP. The SSTs over the Atlantic Ocean are poorly correlated with the upward motion intensity over the TWP (not shown). This result suggests that the changes in global SSTs may be the primary driver of the strengthened Pacific Walker circulation, which leads to enhanced deep convection and intensified upward motion over the TWP.

3.2 Simulated trend of the upward motion over the TWP and its potential mechanism

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To verify the impact of SST on the trend of the upward motion over the TWP, a couple of model simulations are employed in the following analysis. Consistent with the results shown using the reanalysis data (Figs. 2a-c), the simulated 150 hPa *w* (Control run) shows significantly increasing trends over the TWP and decreasing trends over the tropical eastern Pacific in NDJFM during 1958-2017 (Fig. 5a). Additionally, the 150 hPa *w* simulated in the Fixsst run shows weak trends over the TWP (Fig. 5b). The difference between the control and the Fixsst runs suggests that the trends of the 150 hPa *w* over the TWP region is dominated by the changes in the global SSTs during 1958-2017. There are also significantly positive trends of the vertical velocity over the TWP in the lower (700 hPa) and middle troposphere (500 hPa) in the Control run, while the zonal winds are also enhanced over the tropical Pacific. The vertical velocity over the TWP in the Fixsst run shows weak negative trends and the changes in zonal winds over the tropical Pacific are very weak. This confirms the dominant role of the changes in global SSTs on the enhancement of the Walker circulation.

Previous studies found that the changes in the intensity of the Pacific Walker circulation and the stratospheric residual circulation are closely related to the changes in tropical SST (Meng et al., 2012; Tokinaga et al., 2012; Lin et al., 2015). As the SSTs over tropical central and eastern Pacific, and Indian Ocean, show negative correlations with the intensity of the upward motion over the TWP in the lower TTL (Fig. 2f), the warming trends of SSTs over these regions may lead to a weakened upward motion over the TWP. Hence, the warming trends of the SSTs over the TWP

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may be the main factor causing the intensification of the upward motion over the TWP. To verify the impact of the changes in the SSTs over the TWP region on the trends of the upward motion over the TWP, a couple of time-slice runs (R1 and R2) are performed (more details are given in the section 2). The differences of the wind fields between R1 and R2 are shown in Fig. 6. The 150 hPa *w* shows significantly positive anomalies over the TWP and negative anomalies over the tropical eastern Pacific, which is consistent with the trends of the 150 hPa *w* in the Control run and the reanalysis datasets (Figs. 2 and 5). The upward motion in the lower and middle troposphere over the TWP shows intensifying trends due to the enhanced convergence induced by the warmer SSTs over the TWP. This result is consistent with Hu et al. (2016), which suggested that the increased zonal gradient of the SSTs over the tropical Pacific could lead to a strengthened Pacific Walker circulation and an enhanced upward motion over the TWP. Therefore, the warmer SSTs over the TWP could contribute largely to the trend of the upward motion over the TWP in NDJFM during 1958-2017.

The changes in the OLR associated with the changes in the global SSTs are shown in Fig. 7. There are significantly enhanced deep convection as indicated by OLR over the TWP due to the strengthened convergence in the Control run, while the deep convection show weak and even decreasing trends over the TWP in the Fixsst run (Figs. 7a and 7b). The enhanced deep convection over the TWP could lead to the enhancing trends of the upward motion. Hence, it can be inferred that the changes in the global SSTs are responsible for the intensification of the Pacific Walker circulation,

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and the enhanced deep convection and a stronger upward motion over the TWP which could extend to the upper troposphere.

3.3 Implications to the concentrations of water vapor and CO in the TTL and lower stratosphere.

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 trends of CPTT, the 100 hPa streamfunction, and the water vapor concentration in different simulations are displayed in Fig. 7. The changes in the deep convection could lead to the changes in the atmospheric circulation by releasing the latent heat. The changes in the tropical deep convection lead to a Rossby-Kelvin wave response at the UTLS level and then induce the changes in the air temperature near the tropopause (e.g., Gill, 1980; Highwood and Hoskins, 1998). The trends of the 100 hPa streamfunction show a Rossby wave response over the TWP and a Kelvin wave response over the tropical eastern Pacific in the Control run (Fig. 7d), which is caused by the changes in the deep convection over the tropical Pacific. The Rossby-Kelvin wave response further leads to the decreasing trends of the CPTT over the TWP and the increasing trends of the CPTT over the tropical eastern Pacific. Previous studies suggest that the lower stratospheric water vapor is mainly influenced by the coldest temperature near the tropopause (e.g., Garfinkel et al., 2018; Zhou et al., 2021). Since the TWP has the coldest CPTT in the boreal winter (e.g., Pan et al., 2016), the significantly decreased CPTT over the TWP may result in significantly dried lower stratosphere (Fig. 7g). The intensity of the upward motion over the TWP shows negative correlations with

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the concentration of the tropical lower stratospheric water vapor (not shown). Hence, the enhanced upward motion over the TWP may correspond to a dried lower stratosphere. The CPTT shows weak trends over the TWP, and the tropical water vapor shows insignificant trends at 70 hPa in the Fixsst run. The comparison between the Control run and the Fixsst run suggests that the trends of the deep convection, the CPTT, and the lower stratospheric water vapor concentration in the tropics in NDJFM during 1958-2017 are dominated by the trends of the global SSTs, while other external forcings may play minor roles.

Generally, the intensified tropical upwelling may lead to more tropospheric trace gases entering the stratosphere (e.g., Rosenlof, 2003). 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 burming) 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. Here, we utilize the numeric simulations to verify the impact of the strengthened upward motion due to the changes in the global SSTs on the concentrations of the trace gases in the TTL over the TWP. The trends of the CO concentration, which acts as a tropospheric tracer are shown in Fig. 8. The tropical CO at 150 hPa shows significantly increasing trends both in the Control run and the Fixsst run (Figs. 8a and 8b), which suggests that the surface emission of the CO exerts an important effect on the increasing trends of the tropical CO concentration. At the same time, the differences of the CO trends at 150 hPa between the Control run and the Fixsst run are also displayed in Fig. 8c. Since the

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surface emission inventories of the two simulations are the same, it can be inferred that the trends of the CO concentration in Fig. 8c are mainly caused by the changes in the atmospheric circulation induced by the changes in the global SSTs. The difference of the CO concentration at 150 hPa between the Control run and the Fixsst run shows significantly increasing trends over the TWP and decreasing trends over the central Africa, which resembles the trend patterns of the vertical velocity in the lower TTL and the deep convection (Figs. 5i and 7c). This indicates that the enhanced deep convection in the TWP lead to the strengthened upward motion over the TWP, which results in more CO in the upper troposphere over the TWP. It could also be found that CO also increases in the mid latitudes of the southern hemisphere (Fig. 8c). According to previous studies, the CO perturbation from the Indonesian fires at upper troposphere could be transported to the tropical Indian Ocean by easterly winds and then to the subtropics in the southern hemisphere through the southward flow during boreal winter. The CO perturbation then spreads rapidly circling the globe following the subtropical jet (Duncan et al., 2007). 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 (Figs. 5c and f).

The trends of the zonal mean CO concentration from model simulations are displayed in Figs. 9a-c. The zonal mean CO shows significantly increasing trends at all levels in the Control run and the Fixsst run, while the difference of the zonal mean CO between the Control run and the Fixsst run shows significantly increasing trends in the TTL but negative trends in the middle troposphere in the tropics and the

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Northern Hemisphere. At the same time, the difference of CO concentration between the Control run and the Fixsst run averaged in the western Pacific (100°E-180°E) shows significantly increasing trends in the tropics (20°S-10°N) from the surface to the TTL (Fig. 9f). This indicates that the increased zonal mean CO in the TTL (Fig. 9c) is mainly transported through the western Pacific bands. This highlights the importance of the upward motion over the TWP in elevating trace gases from the surface to the upper troposphere.

To understand the CO trends in the Control and Fixsst simulations and their differences, the trends of vertical velocity averaged over the globe and the TWP band are given in Fig. 10. The zonal mean *w* shows weak and even decreasing trends in the tropics while the *w* over the TWP increases in the control run. This is consistent with Fig. 5. While the SSTs fixed to climatological values, the zonal mean *w* shows weak trends and the *w* over the TWP shows significantly decreasing trends. The changes in the global SSTs therefore leads to the increase of the *w* over the TWP region as indicated in the differences between the two simulations in Fig. 10f. In summary, the increase of CO as shown in Figs. 8a-8b is mainly caused by surface emissions. Enhanced tropospheric upward motion over the TWP forced by the changes in the global SSTs, however, leads to some extra increase of CO concentrations in the upper troposphere.

As discussed in the Introduction, the tropospheric trace gases enters the stratosphere mainly through the large-scale tropical upwelling associated with the BD circulation. The trends of the BD circulation in different model simulations as well as

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their differences are displayed in Fig. 11. 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). This is consistent with previous studies (e.g., Rao et al., 2019; Diallo et al., 2021). In the Fixsst run, the trend of w^* is much weaker and not significant in most areas. The changes in the global SSTs therefore play an important role in the intensification of the shallow branch of the BDC as shown by the differences between the two simulations in Fig. 11d. Such strengthened tropical upwelling transports more CO from the upper troposphere to the lower stratosphere as seen in Fig. 9. At the same time, an enhancement of the shallow branch of the BDC also means a stronger meridional transport that contributes to the increase of CO concentration in the subtropics (Fig. 9f). The enhancement of upward motion over the TWP, which transported more tropospheric trace gases to the upper troposphere, works together with the strengthened BD circulation under global warming may lead to an increase of tropospheric trace gases over the TWP in the lower stratosphere.

4 Summary and Discussion

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. An intensified upward motion over the TWP in NDJFM from 1958 to 2017 is detected from both the reanalysis datasets and the model simulations. The trend of the upward motion over the TWP is closely related to the changes in global SSTs, especially the TWP SST warming. Warmer SSTs over the

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TWP lead to a strengthened Pacific Walker circulation, enhanced deep convection and stronger upward motion over the TWP. 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.

Model simulations indicate that the CO concentration increases significantly from the surface to the stratosphere with increased surface emissions. However, an enhancement of tropospheric upward motion and subsequent upward transport of trace gases over the TWP leads to some extra increase of CO concentrations in the upper troposphere. The elevated CO in the upper troposphere is further uplifted to the lower stratosphere by the intensified shallow branch of the BD circulation due mainly to global SST warming and lead to an increase of CO in the lower stratosphere.

Trace gases and aerosols in the stratosphere have important impacts on the stratospheric processes, and hence influence the tropospheric weather and climate through their radiative and dynamical feedback. Our results suggest that the upward motion over the TWP and the vertical component of the BDC at the lower stratosphere level have been intensified. These results suggest that the emission from the maritime continent may play a more important role in the stratospheric processes and the global climate. In addition, more very short lived substances emitted from the tropical ocean could be elevated to the TTL by the enhanced convection and then transported into the stratosphere by the large-scale uplifts and exert important effects on the stratospheric chemistry. However, the quantitative impacts of the intensified upward motion over the TWP on tropospheric and stratospheric trace gases and

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aerosols and their climate feedbacks await further investigation using more observations and model simulations.

Competing interests. The authors declare that they have no conflict of interest.

Author contributions. WT designed the study. WW provided suggestions about the statistical methods and model simulations. KQ ran the models and wrote the first draft. RH, MX, and TW contributed to the manuscript writing. YP provided the data used in the study. All authors contributed to the improvement of the results.

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https://doi.org/10.5194/acp-2021-647
Preprint. Discussion started: 2 September 2021

References:

Andrews, D. G., and Mcintyre, M. E.: Planetary waves in horizontal and vertical shear: the generalized eliassen-palm relation and the mean zonal acceleration, J. Atmos. Sci., 33, 2031 – 2048, 1976

Ashfold, M. J., Pyle, J. A., Robinson, A. D., Meneguz, E., Nadzir, M. S. M., Phang, S. M., Samah, A. A., Ong, S., Ung, H. E., Peng, L. K., Yong, S. E., and Harris, N. R. P.: Rapid transport of East Asian pollution to the deep tropics, Atmos. Chem. Phys., 15, 3565-3573, doi:10.5194/acp-15-3565-2015, 2015.

Bergman, J. W., Jensen, E. J., Pfister, L., and Yang, Q.: Seasonal differences of vertical-transport efficiency in the tropical tropopause layer: On the interplay between tropical deep convection, large-scale vertical ascent, and horizontal circulations, J. Geophys. Res., 117, D05302, doi:10.1029/2011JD016992, 2012.

Brewer, A. M.: Evidence for a world circulation provides by the measurements of helium and water vapor distribution in the stratosphere, Q. J. R. Meteorol. Soc., 75, 351–363, 1949.

Cane, M. A., Clement, A. C., Kaplan, A., Kushnir, Y., Pozdnyakov, D., and Seager, R., et al.: Twentieth-century sea surface temperature trends, Science, 275(5302), 957-960, DOI: 10.1126/science.275.5302.957, 1997.

Deser, C., Phillips, A. S., and Alexander, M. A.: Twentieth century tropical sea surface temperature trends revisited, Geophys. Res. Lett., 37(10), L10701, doi:10.1029/2010GL043321, 2010.

Diallo, M., Ern, M., and Ploeger, F.: The advective Brewer – Dobson circulation in the ERA5 reanalysis: climatology, variability, and trends, Atmos. Chem. Phys., 21, 7515 – 7544, https://doi.org/10.5194/acp-21-7515-2021, 2021.

Dobson G. M. B.: Origin and distribution of the polyatomic molecules in the atmosphere, Proc. R. Soc. Lond. Ser. A. 236: 187-193, 1956.

Duncan, B. N., Logan J. A., Bey, I., Megretskaia, I. A., Yantosca, R. M., Novelli, P. C., Jones, N. B. and Rinsland, C. P.: Global budget of CO, 1988-1997: Source estimates and validation with a global model, J. Geophys. Res., 112, D22301,

https://doi.org/10.5194/acp-2021-647
Preprint. Discussion started: 2 September 2021

doi:10.1029/2007JD008459, 2007.

Fueglistaler, S., Desller, A. E., Dunkerton, T. J., Folkins, I., Fu, Q., and Mote P.: Tropical tropopause layer, Rev. Geophys., 47(1), RG1004, doi:10.1029/2008RG000267, 2009.

Fueglistaler, S., Wernli, H., and Peter, T.: Tropical troposphere-to-stratosphere transport inferred from trajectory calculations, J. Geophys. Res., 109, D03108, doi:10.1029/2003JD004069, 2004.

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., Krüger, K., Lambert, A., Long, C. S., Martineau, P., Molod, A., Monge-Sanz, B. M., Santee, M. L., Tegtmeier, S., Chabrillat, S., Tan, D. G. H., Jackson, D. R., Polavarapu, S., Compo, G. P., Dragani, R., Ebisuzaki, W., Harada, Y., Kobayashi, C., McCarty, W., Onogi, K., Pawson, 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, Atmos. Chem. Phys., 17, 1417-1452, https://doi.org/10.5194/acp-17-1417-2017, 2017

Garfinkel, C. I., Waugh, D. W., and Polvani, L. M.: Recent Hadley cell expansion: The role of internal atmospheric variability in reconciling modeled and observed trends, Geophys. Res. Lett., 42(24), 10824-10831, https://doi.org/10.1002/2015GL066942, 2015

Garfinkel, C. I., Waugh, D. W., Oman, L. D., Wang, L., and Hurwitz, M. M.: Temperature trends in the tropical upper troposphere and lower stratosphere: Connections with sea surface temperatures and implications for water vapor and ozone, J. Geophys. Res., 118, 9658-9672, doi:10.1002/jgrd.50772, 2013.

Garfinkel, C. O., Gordon, A., Oman, L. D., Li, F., Davis, S., and Pawson, S.: Nonlinear response of tropical lower-stratospheric temperature and water vapor to ENSO, Atmos. Chem. Phys., 18, 4597-4615, https://doi.org/10.5194/acp-18-4597-2018, 2018.

Gelaro, R., Mccarty, W., and Suárez, M. J.: The modern-era retrospective analysis for research and applications, version 2 (merra-2), J. Climate, 30(14), 5419-5454, https://doi.org/10.1175/JCLI-D-16-0758.1, 2017

Gettelman, A., Holton, J. R., and Douglass, A. R.: Simulations of water vapor in the lower stratosphere and upper troposphere, J. Geophys. Res., 105(D7), 9003-9023, https://doi.org/10.1029/1999JD901133, 2000.

Gill, A. E.: Some simple solutions for heat-induced tropical circulation, Q. J. R. Meteorolog. Soc., 106, 447-462, doi:10.1002/qj.49710644905, 1980.

Haines, P. E., and Esler, J. G.: Determination of the source regions for surface to stratosphere transport: An Eulerian backtracking approach, Geophys. Res. Lett., 41, 1343-1349, doi:10.1002/2013GL058757, 2014.

Harada, Y., Kamahori, H., Kobayashi, C., Endo, H., Kobayashi, S., Ota, Y., Onoda, H., Onogi, K., Miyaoka, K., and Takahashi, K.: The JRA-55 Reanalysis: Representation of atmospheric circulation and climate variability, J. Meteorol. Soc. Jpn., 94(3), 269-302, https://doi.org/10.2151/jmsj.2016-015, 2016.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., and Nicolas, J., et al.: The ERA5 global reanalysis, Q. J. R. Meteorol. Soc., 146, 1999-2049, DOI: 10.1002/qj.3803, 2020.

Highwood, E. J., and Hoskins, B. J.: The tropical tropopause, Q. J. R. Meteorol. Soc., 124(549), 1579-1604, DOI: 10.1002/qj.49712454911, 1998.

Hitchcock, P.: On the value of reanalyses prior to 1979 for dynamical studies of stratosphere-troposphere coupling, Atmos. Chem. Phys., 19, 2749-2764, https://doi.org/10.5194/acp-19-2749-2019, 2019

Holton, J. R., Haynes, P. H., McIntyre, M. E., Douglass, A. R., Rood, R. B., and Pfister, L.: Stratosphere-troposphere exchange, Rev. Geophys, 33, 403-439, https://doi.org/10.1029/95RG02097, 1995.

Hosking, J. S., Russo, M. R., Braesicke, P., and Pyle, J. A.: Tropical convective transport and the Walker circulation, Atmos. Chem. Phys., 12, 9791-9797, doi:10.5194/acp-12-9791-2012, 2012

Hu, D., Tian, W., Guan, Z., Guo, Y., and Dhomse, S.: Longitudinal asymmetric trends of tropical cold-point tropopause temperature and their link to strengthened Walker circulation, J. Climate, 29(21), 7755–7771,

https://doi.org/10.5194/acp-2021-647
Preprint. Discussion started: 2 September 2021

https://doi.org/10.1175/JCLI-D-15-0851.1, 2016.

Hu, P., Huangfu, J., Chen, W., and Huang, R.: Impacts of early/late South China Sea summer monsoon withdrawal on tropical cyclone genesis over the western North Pacific, Clim. Dynam., 55(19), 1507-1520, https://doi.org/10.1007/s00382-020-05339-7, 2020.

Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., and Onoda, H., et al.: The JRA-55 Reanalysis: General specifications and basic characteristics, J. Meteorol. Soc. Jpn., 93, 5-48, DOI:10.2151/jmsj.2015-001, 2015.

Krüger, K., Tegtmeier, S., and Rex, M.: Long-term climatology of air mass transport through the Tropical Tropopause Layer (TTL) during NH winter, Atmos. Chem. Phys., 8, 813–823, doi:10.5194/acpd-7-13989-2007, 2008.

L'Heureux, M. L., Lee, S., and Lyon, B.: Recent multidecadal strengthening of the Walker circulation across the tropical Pacific, Nat. Clim. Change, 3, 571–576, doi: 10.1038/nclimate1840, 2013.

Levine, J. G., Braesicke, P., Harris, N. R. P., Pyle, J. A.: Seasonal and inter-annual variations in troposphere-to-stratosphere transport from the tropical tropopause layer, Atmos. Chem. Phys., 8, 3689-3703, DOI:10.5194/acpd-8-489-2008, 2008.

Levine, J. G., Braesicke, P., Harris, N. R. P., Savage, N. H., and Pyle, J. A.: Pathways and timescales for troposphere-to-stratosphere transport via the tropical tropopause layer and their relevance for very short lived substances, J. Geophys. Res., 112, D04308, doi:10.1029/2005JD006940, 2007.

Liebmann, B., and Smith, C. A.: Description of a complete (interpolated) outgoing longwave radiation dataset, B. Am. Meteorol. Soc., 77, 1275-1277, doi: 10.1175/1520-0477(1996)077<1255:EA>2.0.CO;2, 1996.

Lin, P., Ming, Y., and Ramaswamy, V.: Tropical climate change control of the lower stratospheric circulation, Geophys. Res. Lett., 42(3), 941-948, doi: 10.1002/2014GL062823, 2015.

Logan, J. A., Megretskaia, I. A., Nassar, R., Murray, L. T., Zhang, L., Bowman, K. W., Worden, H. M., and Luo, M.: Effects of the 2006 El Niño on tropospheric composition as revealed by data from the Tropospheric Emission Spectrometer

(TES), Geophys. Res. Lett., 35, L03816, https://doi.org/10.1029/2007GL031698, 2008.

Lu, J., Vecchi, G. A., and Reichler, T.: Expansion of the Hadley cell under global warming, Geophys. Res. Lett., 34(6), L06805, doi:10.1029/2006GL028443, 2007

Lu, J., Xie, F., Sun, C., Luo, J., Cai, Q., Zhang, J., Li, J., and Tian, H.: Analysis of factors influencing tropical lower stratospheric water vapor during 1980–2017, npj Clim. Atmos. Sci., 3(1), 35, https://doi.org/10.1038/s41612-020-00138-7, 2020.

Ma, S., and Zhou, T.: Robust Strengthening and Westward Shift of the Tropical Pacific Walker Circulation during 1979–2012: A Comparison of 7 Sets of Reanalysis Data and 26 CMIP5 Models, J. Climate, 29, 3097–3118, doi: 10.1175/JCLI-D-15-0398.1, 2016.

Marsh, D. R., Mills, M. J., Kinnison, D. E., Lamarque, J., Calvo, N., and Polvani, L. M.: Climate change from 1850 to 2005 simulated in CESM1 (WACCM), J. Climate, 26, 7372-7391, https://doi.org/10.1175/JCLI-D-12-00558.1, 2013.

McGregor, S., Timmermann, A., Stuecker, M. F., England, M. H., Merrifield, M., Jin, F., and Chikamoto, Y.: Recent Walker circulation strengthening and Pacifific cooling amplified by Atlantic warming, Nat. Clim. Change, 4, 888–882, https://doi.org/10.1038/nclimate2330, 2014.

Meng, Q., Latif, M., Park, W., Keenlyside, N. S., Semenov, V. A., and Martin, T.: Twentieth century Walker circulation change: Data analysis and model experiments, Clim. Dynam., 38, 1757–1773, https://doi.org/10.1007/s00382-011-1047-8, 2012.

Navarro, M. A., Atlas, E. L., Saiz-Lopez, A., Rodriguez-Lloveras, X., Kinnison, D. E., Lamarque, J., Tilmes, S., Filus, M., and Harris, N. R. P., et al.: Airborne measurements of organic bromine compounds in the Pacific tropical tropopause layer, P. Natl. Acad. Sci. USA, 112, 13789-13793, doi:10.1073/pnas.1511463112, 2015.

Newell, R. E., and Gould-Stewart, S.: A stratospheric fountain? J. Atmos. Sci., 38,

https://doi.org/10.5194/acp-2021-647
Preprint. Discussion started: 2 September 2021

Atmospheric Chemistry and Physics Discussions

2789–2796, DOI: 10.1175/1520-0469(1981)038<2789:ASF>2.0.CO;2, 1981.

Newton, R., Vaughan, G., Hintsa, E., Filus, M. T., Pan, L. L., and Honomichl, S., et al.: Observations of ozone-poor air in the tropical tropopause layer, Atmos. Chem. Phys., 18, 5157–5171, https://doi.org/10.5194/acp-18-5157-2018, 2018.

Pan, L. L., Atlas, E. L., Salawitch, R. J., Honomichl, S. B., Bresch, J. F., and Randel, W. J., et al.: The Convective Transport of Active Species in the Tropics (CONTRAST) Experiment, B. Am. Meteorol. Soc., 98(1), 106-128, DOI: 10.1175/BAMS-D-14-00272.1, 2016.

Pan, L. L., Honomichl, S. B., Thornberry, T., Rollins, A., Bui, T. P., Pfister, L., and Jensen E. E.: Observational Evidence of Horizontal Transport-Driven Dehydration in the TTL, Geophys. Res. Lett., 46(13), 7848-7856, DOI: 10.1029/2019GL083647, 2019

Randel, W. J., and Jensen, E. J.: Physical processes in the tropical tropopause layer and their roles in a changing climate, Nat. Geosci., 6, 169–176, DOI:10.1038/ngeo1733, 2013.

Rao, J., Yu, Y., Guo, D., Shi, C., Chen, D., and Hu, D.: Evaluating the Brewer-Dobson circulation and its responses to ENSO, QBO, and the solar cycle in different reanalyses, Earth Planet. Phys., 3(2), 1-16, http://doi.org/10.26464/epp2019012, 2019.

Rayner, N., Parker, D., Horton, E., Folland, C. K., Alexander, L., and Rowell, D. P., et al.: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, J. Geophys. Res., 108(D14), 4407, doi:10.1029/2002JD002670, 2003.

Rosenlof, K. H. How water enters the stratosphere, Science, 302, 1691-1692, doi:10.1126/science.1092703, 2003.

Ryu, J., and Lee, S.: Effect of tropical waves on the tropical tropopause transition layer upwelling, J. Atmos. Sci., 67(10), 3130-3148, DOI: 10.1175/2010JAS3434.1, 2010.

Saiz-Lopez, A., and von Glasow, R.: Reactive halogen chemistry in the troposphere, Chem. Soc. Rev., 41, 6448–6472, DOI:10.1039/c2cs35208g, 2012.

https://doi.org/10.5194/acp-2021-647
Preprint. Discussion started: 2 September 2021

Atmospheric Chemistry and Physics Discussions
Open Access

Schoeberl, M. R., Jensen, E. J., Pfister, L., Ueyama, R., Avery, M., and Dessler, A. E.: Convective hydration of the upper troposphere and lower stratosphere, J. Geophys. Res., 123(9), 4583-4593, https://doi.org/10.1029/2018JD028286, 2018.

Sherwood, S. C.: A stratospheric "drain" over the maritime continent, Geophys. Res. Lett., 27(5), 677-680, https://doi.org/10.1029/1999GL010868, 2000.

Tokinaga, H., Xie, S. P., Deser, C., Kosaka, Y., and Okumura, Y. M.: Slowdown of the Walker circulation driven by tropical Indo-Pacifiic warming. Nature, 491, 439–443, DOI: 10.1038/nature11576, 2012.

Uma, K. N., Das, S. S., Ratnam, M. V., and Suneeth, K. V.: Assessment of vertical air motion among reanalyses and qualitative comparison with very-high-frequency radar measurements over two tropical stations, Atmos. Chem. Phys., 21, 2083-2103, https://doi.org/10.5194/acp-21-2083-2021, 2021.

Wales, P. A., Salawitch, R. J., Nicely, J. M., Anderson, D. C., Canty, T. P. and Baidar, S., et al.: Stratospheric injection of Brominated very short-lived substances: Aircraft observations in the western Pacific and representation in global models, J. Geophys. Res., 123(10), 5690-5719, https://doi.org/10.1029/2017JD027978, 2017.

Wang, S., Schmidt, J. A., Baidar, S., Coburn, S., Dix, B., and Koenig, T. K., et al.: Active and wide-spread halogen chemistry in the tropical and subtropical free troposphere, P. Natl. Acad. Sci. USA, 112, 9281–9286, DOI: 10.1073/pnas.1505142112, 2015.

Wang, W., Matthes, K., and Schmidt, T.: Quantifying contributions to the recent temperature variability in the tropical tropopause layer, Atmos. Chem. Phys., 15, 5815–5826, doi:10.5194/acp-15-5815-2015, 2015.

Wang, W., Matthes, K., Omarani, N.-E., and Latif, M.: Decadal variability of tropical tropopause temperature and its relationship to the Pacific Decadal Oscillation, Sci. Rep., 6, 29537, https://doi.org/10.1038/srep29537, 2016.

Webster, P. J., Lukas, R.: TOGA COARE: the coupled ocean-atmosphere response experiment, B. Am. Meteorol. Soc., 73(9), 1377-1416, DOI: 10.1175/1520-0477(1992)073<1377:TCTCOR>2.0.CO;2, 1992.

https://doi.org/10.5194/acp-2021-647
Preprint. Discussion started: 2 September 2021

Webster, P. J., Clayson, C. A., Curry, J. A.: Clouds, radiation, and the diurnal cycle of sea surface temperature in the tropical western Pacific, J. Climate, 8(8), 1712-1730, DOI: 10.1175/1520-0442(1996)009<1712:CRATDC>2.0.CO;2, 1996.

Xie, F., Li, J., Tian, W., Feng, J., and Huo, Y.: Signals of El Niño Modoki in the tropical tropopause layer and stratosphere, Atmos. Chem. Phys., 12, 5259-5273, doi:10.5194/acp-12-5259-2012, 2012.

Xie, F., Li, J., Tian, W., Li, Y., and Feng, J.: Indo-Pacific Warm Pool Area Expansion, Modoki Activity, and Tropical Cold-Point Tropopause Temperature Variations, Sci. Rep., 4, 4552, https://doi.org/10.1038/srep04552, 2014a.

Xie, F., Li, J., Tian, W., Zhang, J., and Shu, J.: The impacts of two types of El Niño on global ozone variations in the last three decades, Adv. Atmos. Sci., 31(5), 1113-1126, doi: 10.1007/s00376-013-3166-0, 2014b.

Xie, F., Tian, W., Zhou, X., Zhang, J., Xia, Y., and Lu, J.: Increase in lower stratospheric water vapor in the past 100 years related to tropical Atlantic warming, *Geophys. Res. Lett.*, 47, e2020GL090539, DOI: 10.1029/2020GL090539, 2020.

Zhou, X., Chen, Q., Li, Y., Zhao, Y., Lin, Y., and Jiang, Y.: Impacts of the Indo-Pacific warm pool on lower stratospheric water vapor: Seasonality and hemispheric contrasts, J. Geophys. Res., 126, e2020JD034363, DOI: 10.1029/2020JD034363, 2021.

Figure captions:

Fig. 1. The climatological mean (averaged over 1958-2017) values of 150 hPa *w* (10^{-2} m s^{-1}) in different months using the JRA55 reanalysis data.

Fig. 2. The trends of (a) 150 hPa horizontal winds (arrows, units: 10^{-1} m s^{-1} a^{-1}) and vertical velocity (shading, units: 10^{-4} m s^{-1} a^{-1}); (d) 500 hPa horizontal winds (arrows, units: 10^{-1} m s^{-1} a^{-1}) and vertical velocity (shading, units: 10^{-4} m s^{-1} a^{-1}); and (g) 700

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hPa horizontal winds (arrows, units: 10^{-1} m s^{-1} a^{-1}) and vertical velocity (shading, units: 10^{-4} m s^{-1} a^{-1}) from JRA55 in NDJFM during 1958-2017. (b), (e), and (h) are the same as (a), (d), and (g) but for ERA5. (c), (f) and (i) are the same as (a), (d), and (g) except that the trends are during 1980-2017 and the wind field data are from MERRA2. The vertical velocity trends over the dotted regions are statistically significant at the 95% confidence level. The white areas denote missing values.

Fig. 3. 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. The straight lines in each figure indicates the linear trends. The linear trends of the upward motion intensity over the TWP at all levels from three datasets are statistically significant at the 90% confidence level.

Fig. 4. Trends of (a) outgoing longwave radiation (OLR, units: W m^{-2} a^{-1}) during 1974-2017; (b) cold-point tropopause temperature (CPTT, units: 10^{-1} K a^{-1}) and (c) SST (K a^{-1}) during 1958-2017 in NDJFM. (d) The correlation coefficients between the intensity of the upward motion at 150 hPa over the TWP and SST with the linear trends removed. The trends and correlation coefficients over the dotted regions are statistically significant at the 95% confidence level.

Fig. 5. The trends of 150 hPa *w* (shading, units: 10^{-4} m s^{-1} a^{-1}) and horizontal winds (arrows; 10^{-1} m s^{-1} a^{-1}) from (a) Control run; (b) Fixsst run; and (c) difference between the Control run and the Fixsst run in NDJFM during 1958-2017. (d)-(f) are similar to (a)-(c) but for 500 hPa horizontal winds (arrows, units: 10^{-1} m s^{-1} a^{-1}) and vertical

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velocity (shading, units: 10^{-4} m s^{-1} a^{-1}). (g)-(i) are similar to (d)-(f) but for 700 hPa horizontal winds (arrows, units: 10^{-1} m s^{-1} a^{-1}) and vertical velocity (shading, units: 10^{-4} m s^{-1} a^{-1}). The vertical velocity trends over the dotted regions are statistically significant at the 95% confidence level.

Fig. 6. The difference between two time-slice simulations (R1 and R2). Differences of (a) 150 hPa *w* (shading, units: 10^{-2} m s^{-1}) and horizontal winds (arrows, units: m s^{-1}); (b) 500 hPa *w* (shading, units: 10^{-2} m s^{-1}) and horizontal winds (arrows, units: m s^{-1}); (c) 700 hPa *w* (shading, units: 10^{-2} m s^{-1}) and horizontal winds (arrows, units: m s^{-1}) in NDJFM. The differences between vertical velocity over the dotted regions are statistically significant at the 95% confidence level.

Fig. 7. The trends of outgoing longwave radiation (OLR; units: W m^{-2} a^{-1}) from (a) Control run; (b) Fixsst run; and (c) difference between the Control run and the Fixsst run in NDJFM during 1958-2017. (d)-(f) are similar to (a)-(c) but for CPTT (shading, units: 10^{-1} K a^{-1}) and 100 hPa streamfunction (contour, units: 10^6 m^2 s^{-1} a^{-1}). (g)-(i) are similar to (d)-(f) but for 70 hPa water vapor concentration (units: 10^{-2} ppmv a^{-1}). The trends in (a)-(c) and (g)-(i) over the dotted regions are statistically significant at the 95% confidence level. The CPTT trends in (d)-(f) over the dotted regions are statistically significant at the 95% confidence level.

Fig. 8. The trends of 150 hPa CO concentration (10^{-4} ppmv a^{-1}) from (a) Control run; (b) Fixsst run; and (c) difference between the Control run and the Fixsst run in NDJFM during 1958-2017. The trends in (a)-(c) over the dotted regions are statistically significant at the 95% confidence level.

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Fig. 9. Latitude-pressure cross sections of the trends of the zonal mean CO concentration (10^{-4} ppmv a^{-1}) from (a) Control run; (b) Fixsst run; and (c) difference between the Control run and the Fixsst run in NDJFM during 1958-2017. (d)-(f) are the same as (a)-(c) but for the CO concentration averaged over the TWP (100°E-180°E). The trends over the dotted regions are statistically significant at the 95% confidence level.

Fig. 10. Latitude-pressure cross sections of the trends of the zonal mean *w* (10^{-4} m s^{-1} a^{-1}) and *v* (10^{-1} m s^{-1} a^{-1}) from (a) Control run; (b) Fixsst run; and (c) difference between the Control run and the Fixsst run in NDJFM during 1958-2017. (d)-(f) are similar to the (a)-(c) but for the trends of the *w* (10^{-4} m s^{-1} a^{-1}) and *v* (10^{-1} m s^{-1} a^{-1}) over the TWP (100°E-180°E). The shadings denote the trends of the *w* (10^{-4} m s^{-1} a^{-1}). The trends over the dotted regions are statistically significant at the 90% confidence level.

Fig. 11. Latitude-pressure cross sections of the trends of the BD circulation (vectors, units in the horizontal and vertical components are 10^{-2} and 10^{-5} m s^{-1} a^{-1}, respectively) from (a) Control run; (b) Fixsst run; (c) difference between the Control run and the Fixsst run; and (d) JRA55. 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.

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Figures

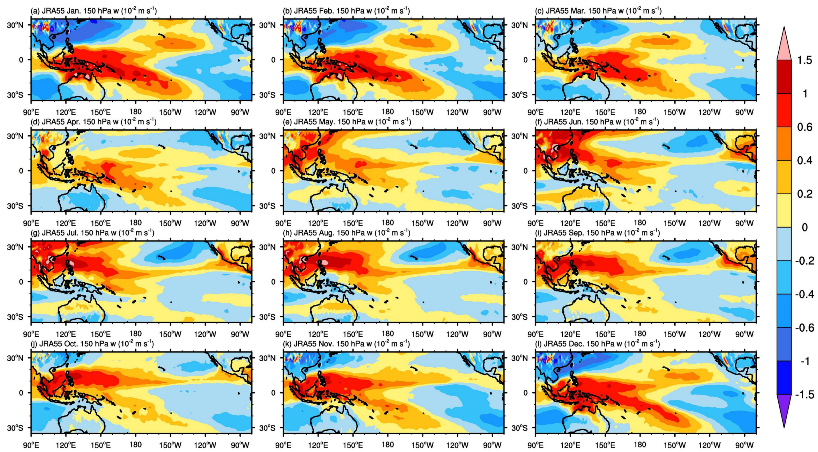

Fig. 1. The climatological mean (averaged over 1958-2017) values of 150 hPa *w* (10^{-2} m s^{-1}) in different months using the JRA55 reanalysis data.

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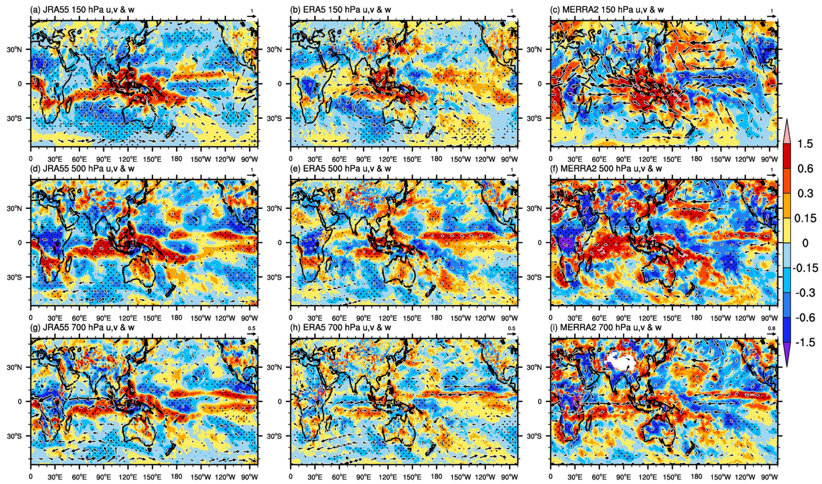

Fig. 2. The trends of (a) 150 hPa horizontal winds (arrows, units: 10^{-1} m s^{-1} a^{-1}) and vertical velocity (shading, units: 10^{-4} m s^{-1} a^{-1}); (d) 500 hPa horizontal winds (arrows, units: 10^{-1} m s^{-1} a^{-1}) and vertical velocity (shading, units: 10^{-4} m s^{-1} a^{-1}); and (g) 700 hPa horizontal winds (arrows, units: 10^{-1} m s^{-1} a^{-1}) and vertical velocity (shading, units: 10^{-4} m s^{-1} a^{-1}) from JRA55 in NDJFM during 1958-2017. (b), (e), and (h) are the same as (a), (d), and (g) but for ERA5. (c), (f) and (i) are the same as (a), (d), and (g) except that the trends are during 1980-2017 and the wind field data are from MERRA2. The vertical velocity trends over the dotted regions are statistically significant at the 95% confidence level. The white areas denote missing values.

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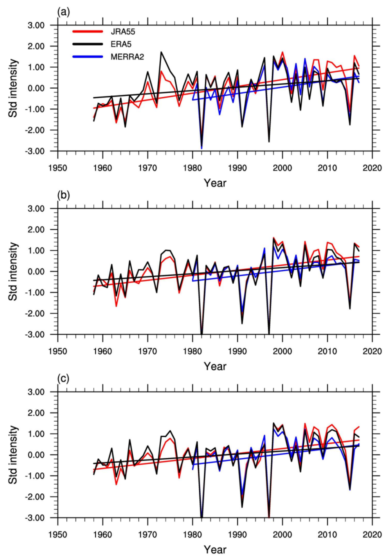

Fig. 3. The time series of the standardized intensity of the upward motion over the tropical western Pacific (20°S-10°N, 100°E-180°E) at (a) 150 hPa; (b) 500 hPa; and (c) 700 hPa extracted from JRA55 (red), ERA5 (black) and MERRA2 (blue) datasets. The straight lines in each figure indicates the linear trends. The linear trends of the upward motion intensity over the TWP at all levels from three datasets are statistically significant at the 90% confidence level.

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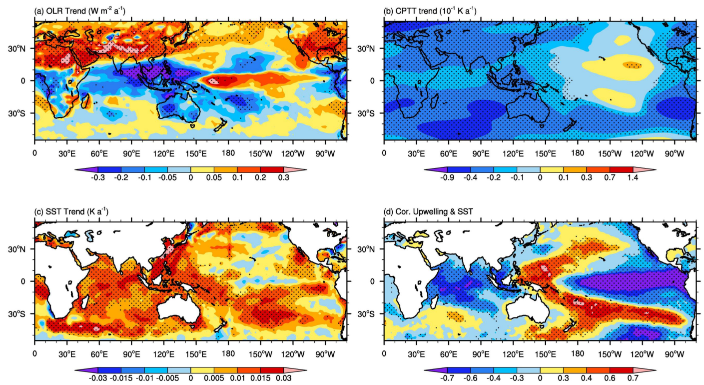

Fig. 4. Trends of (a) outgoing longwave radiation (OLR, units: W m^{-2} a^{-1}) during 1974-2017; (b) cold-point tropopause temperature (CPTT, units: 10^{-1} K a^{-1}) and (c) SST (K a^{-1}) during 1958-2017 in NDJFM. (d) The correlation coefficients between the intensity of the upward motion at 150 hPa over the TWP and SST with the linear trends removed. The trends and correlation coefficients over the dotted regions are statistically significant at the 95% confidence level.

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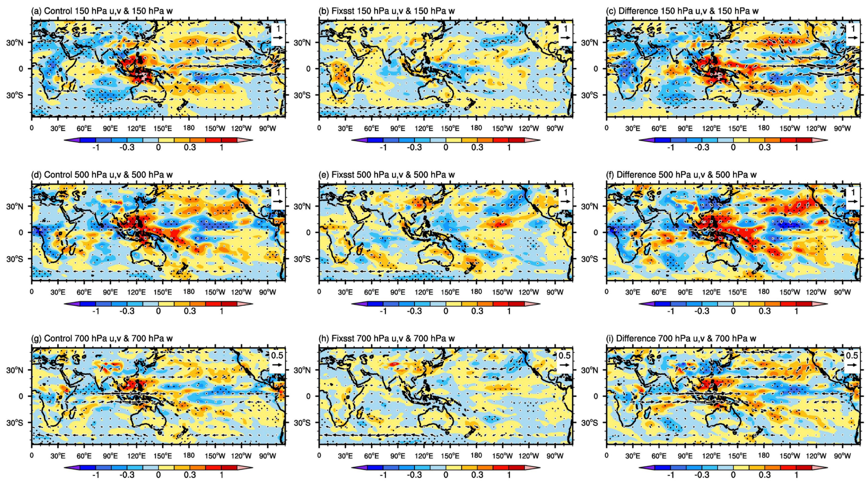

Fig. 5. The trends of 150 hPa *w* (shading, units: 10^{-4} m s^{-1} a^{-1}) and horizontal winds (arrows; 10^{-1} m s^{-1} a^{-1}) from (a) Control run; (b) Fixsst run; and (c) difference between the Control run and the Fixsst run in NDJFM during 1958-2017. (d)-(f) are similar to (a)-(c) but for 500 hPa horizontal winds (arrows, units: 10^{-1} m s^{-1} a^{-1}) and vertical velocity (shading, units: 10^{-4} m s^{-1} a^{-1}). (g)-(i) are similar to (d)-(f) but for 700 hPa horizontal winds (arrows, units: 10^{-1} m s^{-1} a^{-1}) and vertical velocity (shading, units: 10^{-4} m s^{-1} a^{-1}). The vertical velocity trends over the dotted regions are statistically significant at the 95% confidence level.

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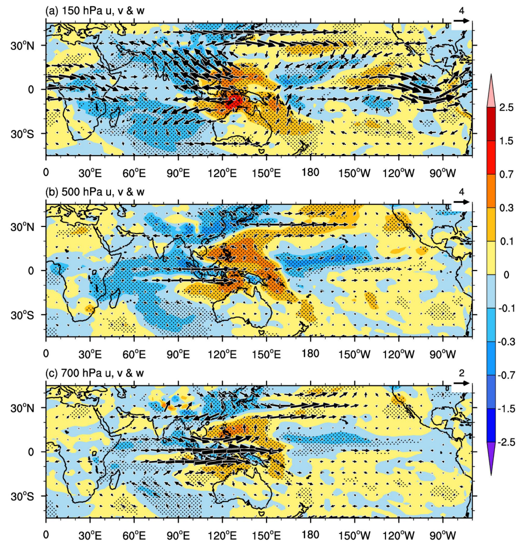

Fig. 6. The difference between two time-slice simulations (R1 and R2). Differences of (a) 150 hPa *w* (shading, units: 10^{-2} m s^{-1}) and horizontal winds (arrows, units: m s^{-1}); (b) 500 hPa *w* (shading, units: 10^{-2} m s^{-1}) and horizontal winds (arrows, units: m s^{-1}); (c) 700 hPa *w* (shading, units: 10^{-2} m s^{-1}) and horizontal winds (arrows, units: m s^{-1}) in NDJFM. The differences between vertical velocity over the dotted regions are statistically significant at the 95% confidence level.

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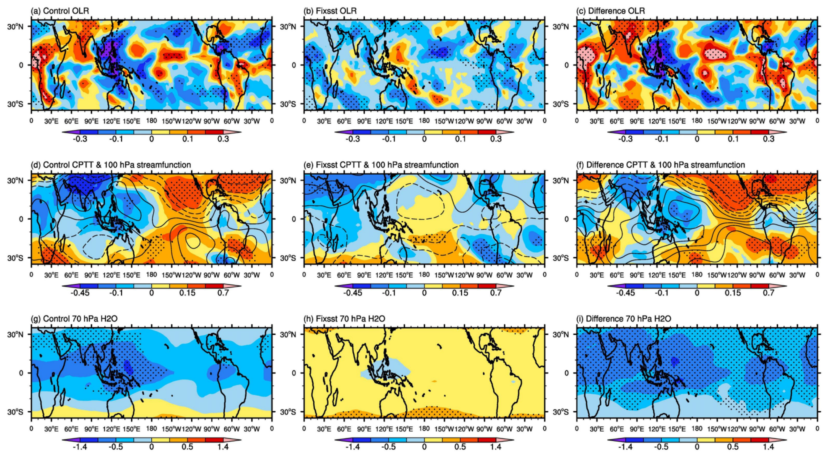

Fig. 7. The trends of outgoing longwave radiation (OLR; units: W m^{-2} a^{-1}) from (a) Control run; (b) Fixsst run; and (c) difference between the Control run and the Fixsst run in NDJFM during 1958-2017. (d)-(f) are similar to (a)-(c) but for CPTT (shading, units: 10^{-1} K a^{-1}) and 100 hPa streamfunction (contour, units: 10^{6} m^{2} s^{-1} a^{-1}). (g)-(i) are similar to (d)-(f) but for 70 hPa water vapor concentration (units: 10^{-2} ppmv a^{-1}). The trends in (a)-(c) and (g)-(i) over the dotted regions are statistically significant at the 95% confidence level. The CPTT trends in (d)-(f) over the dotted regions are statistically significant at the 95% confidence level.

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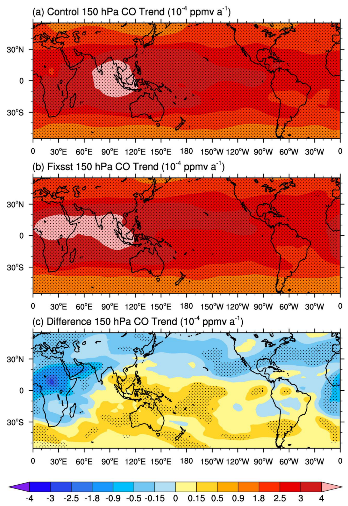

Fig. 8. The trends of 150 hPa CO concentration (10^{-4} ppmv a^{-1}) from (a) Control run; (b) Fixsst run; and (c) difference between the Control run and the Fixsst run in NDJFM during 1958-2017. The trends in (a)-(c) over the dotted regions are statistically significant at the 95% confidence level.

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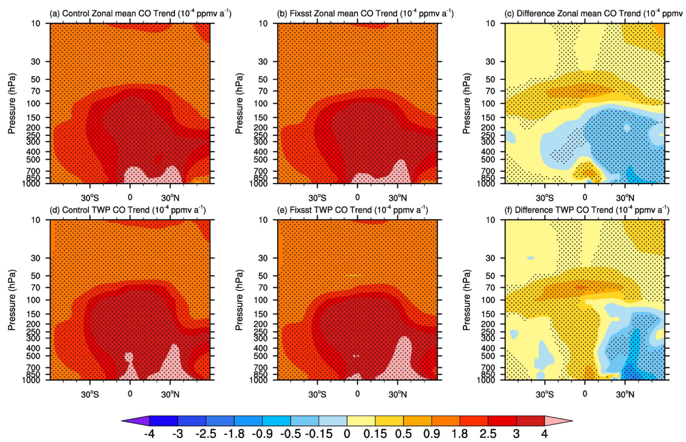

Fig. 9. Latitude-pressure cross sections of the trends of the zonal mean CO concentration (10^{-4} ppmv a^{-1}) from (a) Control run; (b) Fixsst run; and (c) difference between the Control run and the Fixsst run in NDJFM during 1958-2017. (d)-(f) are the same as (a)-(c) but for the CO concentration averaged over the TWP (100°E-180°E). The trends over the dotted regions are statistically significant at the 95% confidence level.

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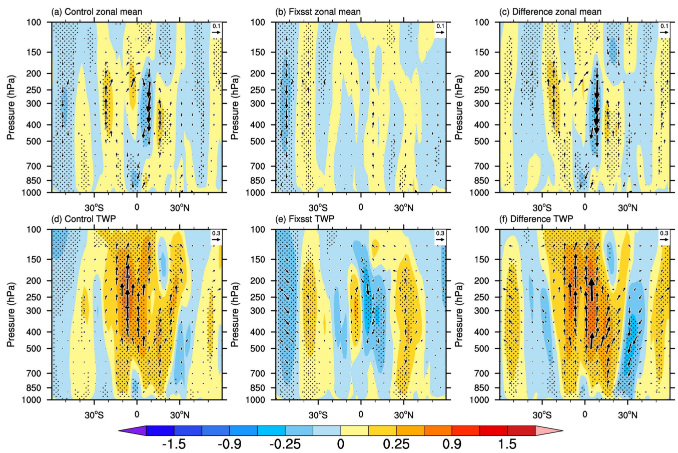

Fig. 10. Latitude-pressure cross sections of the trends of the zonal mean *w* (10^{-4} m s^{-1} a^{-1}) and *v* (10^{-1} m s^{-1} a^{-1}) from (a) Control run; (b) Fixsst run; and (c) difference between the Control run and the Fixsst run in NDJFM during 1958-2017. (d)-(f) are similar to the (a)-(c) but for the trends of the *w* (10^{-4} m s^{-1} a^{-1}) and *v* (10^{-1} m s^{-1} a^{-1}) over the TWP (100°E-180°E). The shadings denote the trends of the *w* (10^{-4} m s^{-1} a^{-1}). The trends over the dotted regions are statistically significant at the 90% confidence level.

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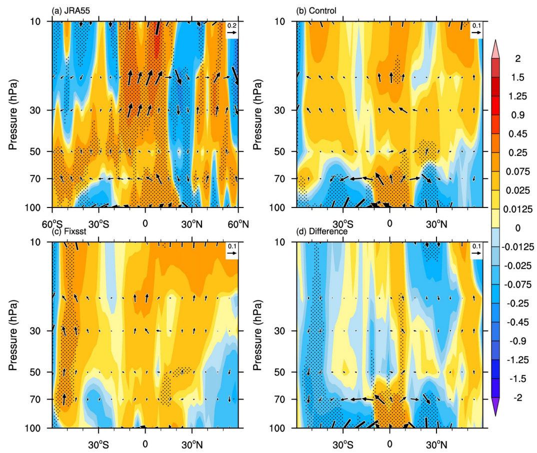

Fig. 11. Latitude-pressure cross sections of the trends of the BD circulation (vectors, units in the horizontal and vertical components are 10^{-2} and 10^{-5} m s^{-1} a^{-1}, respectively) from (a) Control run; (b) Fixsst run; (c) difference between the Control run and the Fixsst run; and (d) JRA55. 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.