# The influence of the stratospheric quasi-biennial oscillation on the tropical easterly jet over the Maritime Continent

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**Abstract**

This study investigated the influence of the stratospheric quasi-biennial oscillation (QBO) on the tropical easterly jet (TEJ). Easterly (EQBO) and westerly (WQBO) phases of the QBO are defined based on the 50 hPa zonal wind. The climatological rising movement on the west side of the Maritime Continent can reach higher altitude than that on the east side, which makes the convection on the west side more effectively promoted by the reduced stability near the tropopause during EQBO. Compared with WQBO, during EQBO, the convection on the west (east) side of the Maritime Continent is enhanced (weakened), and there is a stronger (weaker) divergence in the upper troposphere. Corresponding to the change of the divergence field, the TEJ over the Maritime Continent during EQBO is significantly weakened than WQBO, and the magnitude of the change can reach 11% of the climatological TEJ.

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**Key Points:**

Main point #1:
TEJ is weakened over the Maritime Continent during easterly phase QBO.

Main point #2:
QBO regulates TEJ by modulating the stability near the tropopause and the convection over the Maritime Continent.

Main point #3:
Different convection heights between the east and west sides of the Maritime Continent lead to different responses to QBO.

## Abstract

This study investigated the influence of the stratospheric quasi-biennial oscillation (QBO) on the tropical easterly jet (TEJ). Easterly (EQBO) and westerly (WQBO) phases of the QBO are defined based on the 50 hPa zonal wind. The climatological rising movement on the west side of the Maritime Continent can reach higher altitude than that on the east side, which makes the convection on the west side more effectively promoted by the reduced stability near the tropopause during EQBO. Compared with WQBO, during EQBO, the convection on the west (east) side of the Maritime Continent is enhanced (weakened), and there is a stronger (weaker) divergence in the upper troposphere. Corresponding to the change of the divergence field, the TEJ over the Maritime Continent during EQBO is significantly weakened than WQBO, and the magnitude of the change can reach 11% of the climatological TEJ.

## Plain Language Summary

The tropical easterly jet (TEJ) is an essential component of the Asian monsoon system. Quasi-biennial oscillation (QBO) is a phenomenon characterized by quasi-periodic oscillation in the tropical stratospheric wind field. The opposite east-west wind directions in the lower stratosphere during different phases of QBO are accompanied by opposite temperature and stability anomalies around the tropopause. Due to the different heights of the rising movements on the east and west sides of the Maritime Continent, their responses to the change of upper tropospheric stability caused by QBO are different. Responding to the change of the rising movement, the TEJ over the Maritime Continent during easterly phase of QBO is significantly weakened compared with westerly phase of QBO, and the decrease magnitude can reach 11% of the climatological TEJ. Considering that QBO has a relatively robust periodicity, the relationship between QBO and TEJ has potential merit for long-range prediction of TEJ and weather systems related to the Asian monsoon.

**Keywords:** quasi-biennial oscillation; tropical easterly jet; tropical convection

## 1. Introduction

The tropical easterly jet (TEJ) has a strong easterly wind center in the upper troposphere over the Indian Ocean in boreal summer. The maximum wind speed of the Indian Ocean TEJ can reach above 20 m/s (*Huang et al.*, 2020). TEJ results from the thermal contrast between the Asian continent and the Ocean and is enhanced by the local thermal effect of the Tibetan Plateau (*Koteswaram*, 1958). TEJ is an important component of the Asian monsoon system (*Krishnamurti and Bhalme*, 1976) and has an essential effect on the weather and climate in the region influenced by monsoons, e.g., the high-cloud amount in the Asian monsoon region (*Sathiyamoorthy et al.*, 2004), the Tropical Cyclonic Systems in the Bay of Bengal (*Rao et al.*, 2004), Indian summer monsoon rainfall (*Huang et al.*, 2021), summer rainfall of eastern Africa (*Vashisht et al.*, 2021), et al.. The Maritime Continent is the entrance of the Indian Ocean TEJ. The TEJ intensity over the Maritime Continent and tropical cyclone genesis frequency over the Western North Pacific have a positive relationship (*Zhan et al.*, 2022). The TEJ is located in the upper troposphere and can extend to the bottom of the stratosphere. Previous studies have focused on the influence from the troposphere on TEJ (*Chen and van Loon*, 1987; *Huang et al.*, 2019; *Lu and Ding*, 1989; *Pattanaik and Satyan*, 2000; *Tanaka*, 1982), but it is still unclear whether the stratosphere plays a role in it.

The mean zonal winds of the equatorial stratosphere switch between easterly and westerly winds with periods varying from about 24 to 30 months, which is named the quasi-biennial oscillation (QBO) (*Holton and Hakim*, 2013). The associated stratospheric wind field has zonal uniformity along the equator and is symmetrical about the equator. QBO is driven by tropical atmospheric disturbances such as Kevin waves, Rossby-gravity waves, and Inertia-gravity waves with periods much smaller than QBO (*Baldwin et al.*, 2001; *Dunkerton*, 1997; *Plumb*, 1977). The fact that QBO is confined near the equator in the stratosphere rather than in the extratropic is due to the smaller Coriolis torque near the equator (*Lindzen and Holton*, 1968; *Scott and Haynes*, 1998). There are many studies on the effects of QBO on the tropical tropospheric weather systems (more detailed introduction are in the latter text), e.g., Madden-Julian oscillation (MJO) (*Back et al.*, 2020; *Martin et al.*, 2021; *Son et al.*, 2017), the boreal summer monsoon (*Giorgetta et al.*, 1999; *Rai and Dimri*, 2017), and tropical deep convection (*Liess and Geller*, 2012; *Nie and Sobel*, 2015).

QBO is one of the most predictable variations of the tropical atmosphere (Hamilton et al. 2015) and TEJ is an important member of the Asian monsoon system, therefore exploring the relationship between QBO and TEJ may have the potential to improve the longer-range forecasting skills of the summer Asian monsoon system. The influence of the stratosphere on the boreal troposphere in winter is extensively studied, for example, the QBO-MJO relationship is more significant in winter (*Wang et al.*, 2019), while the relationship between the summer stratosphere and members of the Asian monsoon system such as TEJ is worth studying.

## 2. Data and method

The summer mean (June to August) of the zonal wind at 50 hPa (U50) observed at the Singapore radiosonde station (1°N/104°E) are used to define the QBO phases. When the standardized U50 is less than half of its standard deviation, then the summer is defined as EQBO. When the standardized U50 is greater than half of its standard deviation, then the summer is defined as WQBO. EQBO and WQBO years are shown in Table 1. The time evolution of the zonal mean zonal wind at 50 hPa at different latitudes is shown in Figure 1. The Meteorological fields analyzed in this study are based on ERA5 provided by ECMWF (*Hersbach et al.*, 2020). NOAA Climate Data Record of Monthly Outgoing Longwave Radiation (OLR) (CDR OLR; Hai-Tien Lee and NOAA Climate Data Record Program, 2018) is used to analyze convection.

A Monte Carlo test has been applied to test the statistical significance of the difference between EQBO and WQBO. We randomly subsampled M and N elements from all years and obtain the difference between the two subsets. M and N are the number of EQBO and WQBO years, respectively. We repeated this random selection process 10,000 times to obtain a probability density function. The significance of the difference was estimated using the density function. Anomalies of EQBO/WQBO from the climatology were also tested by Monte Carlo method.

## 3. Result

The patterns of tropical upper tropospheric zonal wind anomalies of EQBO and WQBO are similar but with the opposite signs. There are westerly wind anomalies at 150 hPa over the Maritime Continent where the climatological entrance of the summer TEJ locates during EQBO (Figures 2a and 2c), while there are slightly easterly wind anomalies during WQBO (Figures 2b and 2d). Figure 2 implies the TEJ over the Maritime Continent during EQBO is weaker than that during WQBO. Sectioned from 120°E, the vertical structures of the zonal wind anomalies during EQBO and WQBO show that the zonal wind anomalies above 100 hPa in the stratosphere reflect typical QBO characteristics (*Baldwin et al.*, 2001). In the middle and lower stratosphere, the maximum values of the zonal wind anomalies are located at 10 and 50 hPa at the equator. In the upper troposphere, the maximum values of the zonal wind anomalies are located at 150-200 hPa over the Maritime Continent. The wind anomalies in the stratosphere have strong zonally uniformity along the equator, while the wind anomalies in the troposphere do not have such zonally uniformity. The average value of U50 during EQBO is -18.1 m/s, while that during WQBO is 9.9 m/s, and its absolute value is about half of that of EQBO. Similarly, the absolute value of zonal wind anomalies at upper troposphere over the Maritime Continent during WQBO are about half of that during EQBO. The correlation coefficient between the year-to-year time series of U50 and the zonal wind averaged in the box region at 120°E (box region shown in Figures 2c and 2d) is -0.34, significant at the 95% confident level under t-test, indicating a close relationship between QBO and TEJ over Maritime Continent.

The rainfall plays an important role in regulating TEJ variability (*Kanamitsu et al.*, 1972; *Rao and Srinivasan*, 2016; *Sathiyamoorthy et al.*, 2007), which implies the convection and rising movement in the tropics have an important impact on the variation of TEJ. Figure 3 shows the differences in the convection between EQBO and WQBO. Summer tropical rising and convection are strongest in the Bay of Bengal and Maritime Continent. Both the observed OLR (Figure 3b) and reanalysis ω (Figure 3d) show that convections on the west side of the Maritime Continent during EQBO are stronger than that during WQBO, while convections on the east side of the Maritime Continent during EQBO are weaker than that during WQBO.

During EQBO, the convective enhancement area on the west side of the Maritime Continent is accompanied by the increase of the upper tropospheric divergence, and the convective weakening area on the east side of the Maritime Continent is accompanied by the decrease of the upper tropospheric divergence (Figure 3e). Figure 3f shows the differences in atmospheric circulation along with the equatorial profile between EQBO and WQBO. Compared with WQBO, during EQBO, the rising movement on the west side of the Maritime Continent is stronger, and the rising movement on the east side of the Maritime Continent is weakened, resulting in westerly wind anomalies in the upper troposphere, which is consistent with the divergence change in the upper troposphere. The westerly wind anomalies lead to the weakness of the TEJ over the Maritime Continent.

The effects of QBO on tropical convection have been addressed in recent studies on the relationship between QBO and intraseasonal oscillations, including the Madden Julian Oscillation (MJO) (*Jiang et al.*, 2020; *Nishimoto and Yoden*, 2017; *Son et al.*, 2017; *Wang and Wang*, 2021; *Yoo and Son*, 2016) and Boreal Summer Intraseasonal Oscillation (BSISO) (*Wang et al.*, 2019). Previous studies provide some mechanisms by which QBO regulates tropical convection (*Martin et al.*, 2021). The equatorial westerly and easterly wind shears in the lower stratosphere appear with warm and cold temperature anomalies, respectively (*Holton and Hakim*, 2013). The wind shear anomalies during EQBO would uplift the tropical tropopause and lead to ascension and a cooler tropopause, while the opposite scenario applies for WQBO (*Collimore et al.*, 2003). The QBO-stratification mechanism (*Collimore et al.*, 2003; *Giorgetta et al.*, 1999; *Gray et al.*, 1992; *Liess and Geller*, 2012; *Nie and Sobel*, 2015) states that EQBO could destabilize the upper troposphere and lower stratosphere, promoting more vigorous deep convection. If the vertical extent of the convection related with the QBO increases, there would be larger convective horizontal extent and more cloud amount (*Gray et al.*, 1992). Figure 4 shows that the tropospheric stability above 150 hPa during EQBO is less than that during WQBO, which are the cases on both sides of the Maritime Continent.. Although Figure 4 analyzed the effect of QBO on the stability in summer, the results here are consistent with the mechanism of QBO affecting stability in winter, and the model simulations also support this result (*Martin et al.*, 2019; *Nie and Sobel*, 2015).

During EQBO, the stability above 150 hPa is reduced consistently on both sides of the Maritime Continent, but the convection and rising movement on the east and west sides of the Maritime Continent change inconsistently. Only about 1% of tropical convective systems can reach above 150 hPa (*Liu and Zipser*, 2005). *Nishimoto and Yoden* (2017) stated that only the deep convection developed very high can be affected by the stability conditions near the tropopause. Inspired by their work, the difference in the heights of the rising movement between the east and west sides of the Maritime Continent is investigated. Figure 3f shows that the climatological rising movement west of 120°E in the equatorial region can reach above 150 hPa, while the rising movement east of 120°E cannot reach 150 hPa. This implies that even if EQBO causes a decrease in stability around the tropopause, only convections on the west side of the Maritime Continent can effectively take advantage of this condition to furtherly develop.

In addition to the impact of the climatological rising height difference between the two sides of the Maritime Continent, there are differences in stability at 300-150 hPa between the two sides of the Maritime Continent. The stability at 300-150 hPa at 90°E (west of the Maritime Continent) during EQBO is smaller than that of WQBO (Figure 4a), while the stability at 300-150 hPa at 140°E (east of the Maritime Continental) during EQBO is slightly larger than that of WQBO (Figure 4b). The smaller stability contributes to the development of convection, so the rising movement on the west side of the Maritime Continent is enhanced while the rising movement on the east side of the Maritime Continent is weakened during the EQBO compared with the WQBO.

## 4. Summary

In this study, the effects of different phases of stratospheric QBO on the summer TEJ were investigated. During EQBO, the rising movement on the west side of the Maritime Continent is enhanced while that on the east side of the Maritime Continent is weakened. The changes in the rising movement lead to the enhancement of the divergence on the west side of the Maritime Continent and the decrease of the divergence on the east side of the Maritime Continent in the upper equatorial troposphere, which results in the decrease of TEJ over the Maritime Continent. While the opposite scenario applies for WQBO. EQBO has a greater effect on TEJ over the Maritime Continent than WQBO, because the easterly wind at 50 hPa at the equator can reach a maximum of 24 m/s during EQBO summer, while the westerly wind at 50 hPa can only reach a maximum of 13 m/s during WQBO summer. The contribution of QBO to the changes of TEJ is important, since the difference in TEJ over the Maritime Continent between EQBO and WQBO can reach 17% of the climatological intensity of TEJ (see Table 1, calculated by $[TEJ_{EQBO}-TEJ_{WQBO}]/TEJ_{CLIMATE}$). The correlation coefficient between the U50 of QBO and the strength of TEJ over the Maritime Continent is -0.34, although it is not very high, it passed the significance test, which implies that QBO is a potential contribution factor for seasonally forecasting TEJ.

About 0.1% of tropical convective systems can penetrate above 100 hPa (*Liu and Zipser*, 2005), due to the weak vertical movement around the tropopause, although the TEJ is located in the upper troposphere and is very close to the QBO wind field in the lower stratosphere, it is difficult to directly connect the QBO wind anomaly with the TEJ through the momentum exchange of the vertical movement. We propose that QBO affects TEJ by changing the upper tropospheric stability and tropical convections. The mechanism of the relationship between QBO and convection has been proposed and confirmed by many previous studies. The question that this study needs to explain is why the convections on the east and west sides of the Maritime Continent have opposite changes during different phases of QBO. We found that the climatological rising movement on the west side of the Maritime Continent (west of 120°E) can reach above 150 hPa, but that on the east side of the Maritime Continent cannot. This climatological characteristic makes the convection on the west side more effective in taking advantage of the reduced stability near the tropopause during EQBO. In addition, EQBO reduces the stability at 300-150 hPa on the west side of the Maritime Continent rather than the east side, which is also conducive to the rising movement development on the west side of the Maritime Continent.

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## Competing interests

The Authors declare no Competing Financial or Non-Financial Interests.

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## Figures

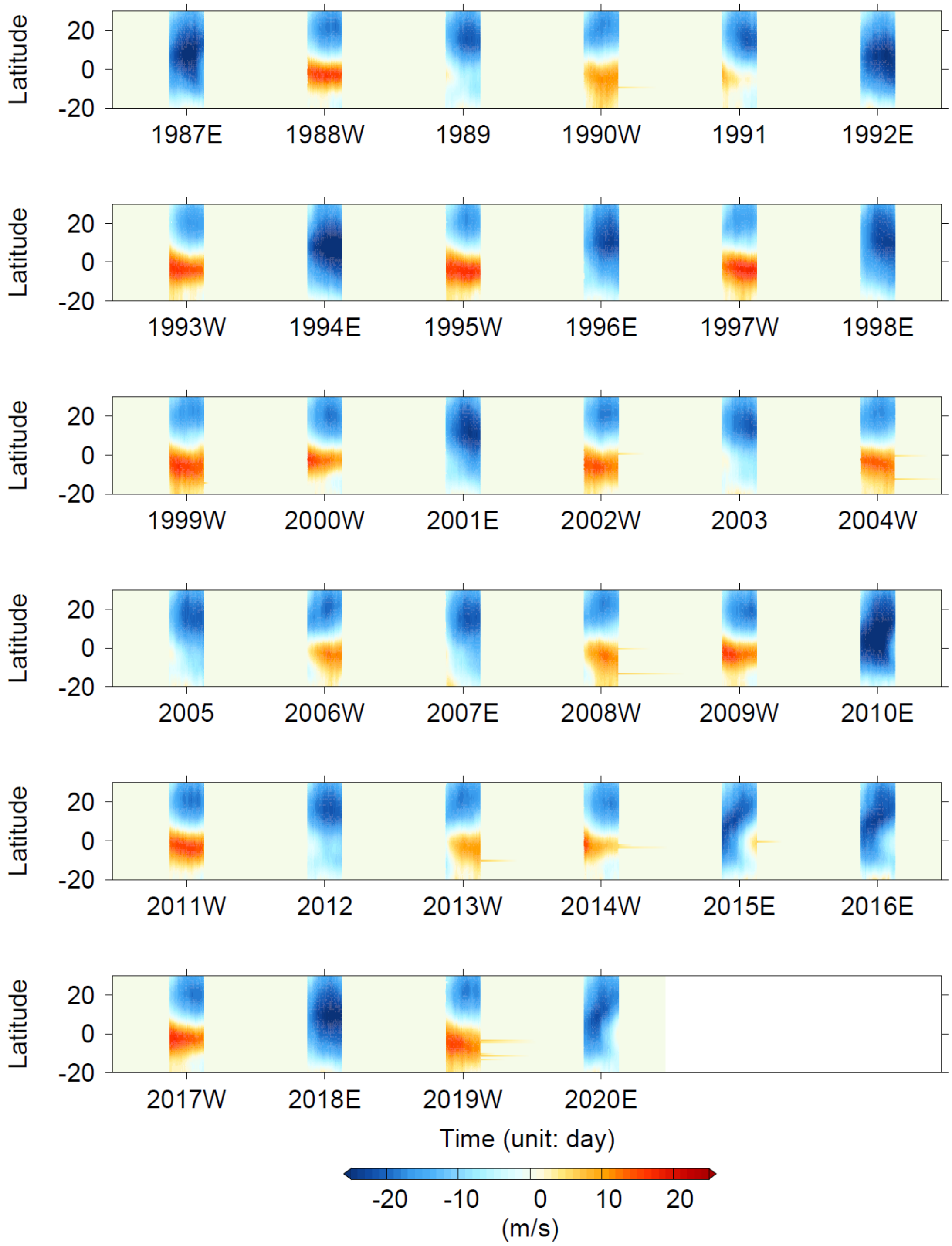


**Fig. 1** 50 hPa zonal mean zonal wind during June to August derived from ERA5. The resolution of the abscissa is the day, only the corresponding year is marked. The QBO phases are labeled next to the years.

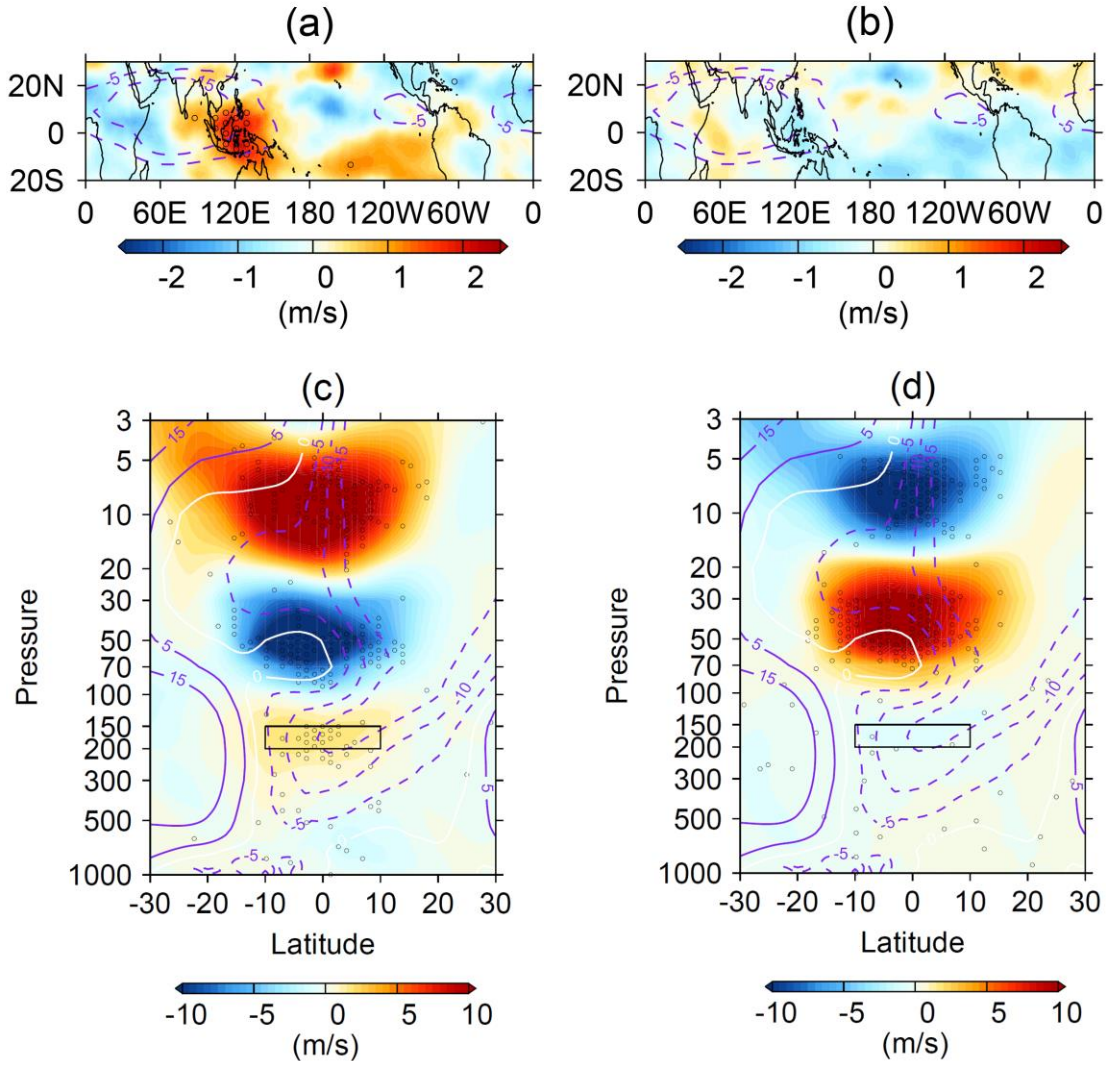


**Fig. 2** Summer mean zonal wind anomalies from climatology at 150 hPa during (a) EQBO and (b) WQBO. Zonal wind anomalies at 120°E during (c) EQBO and (d) WQBO. The climatological zonal wind is shown by purple contour lines. The regions with empty dots exceed the 95% confidence level under the Monte Carlo test. The range of the black box in (c) and (d) is 10°N-10°S, 150-200 hPa.

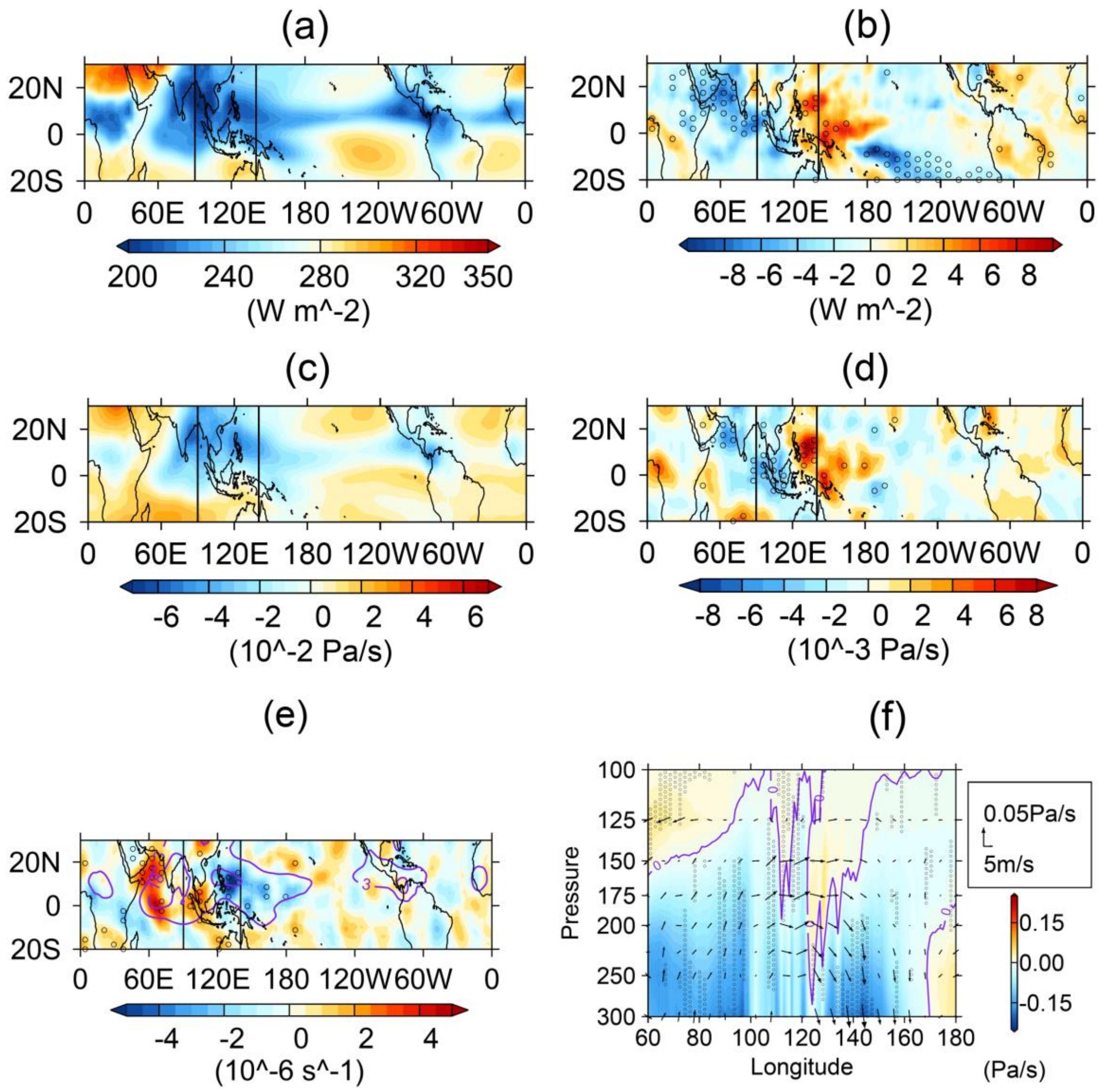


**Fig. 3** (a) Climatology of OLR and (b) difference in OLR between EQBO and WQBO. (c) Climatology 200 hPa ω and (d) difference in 200 hPa ω between EQBO and WQBO. (e) Climatology of divergence at 150 hPa (contours with values of 3 and 18 $10^{-6}$ $s^{-1}$) and difference in divergence between EQBO and WQBO (filled color). The black lines mark 90°E and 140°E. (f) Differences in u and ω along the equator between EQBO and WQBO (vectors). Differences in ω are statistically tested. Climatology of ω along the equator (filled color). The regions with empty dots exceed the 95% confidence level under the Monte Carlo test.

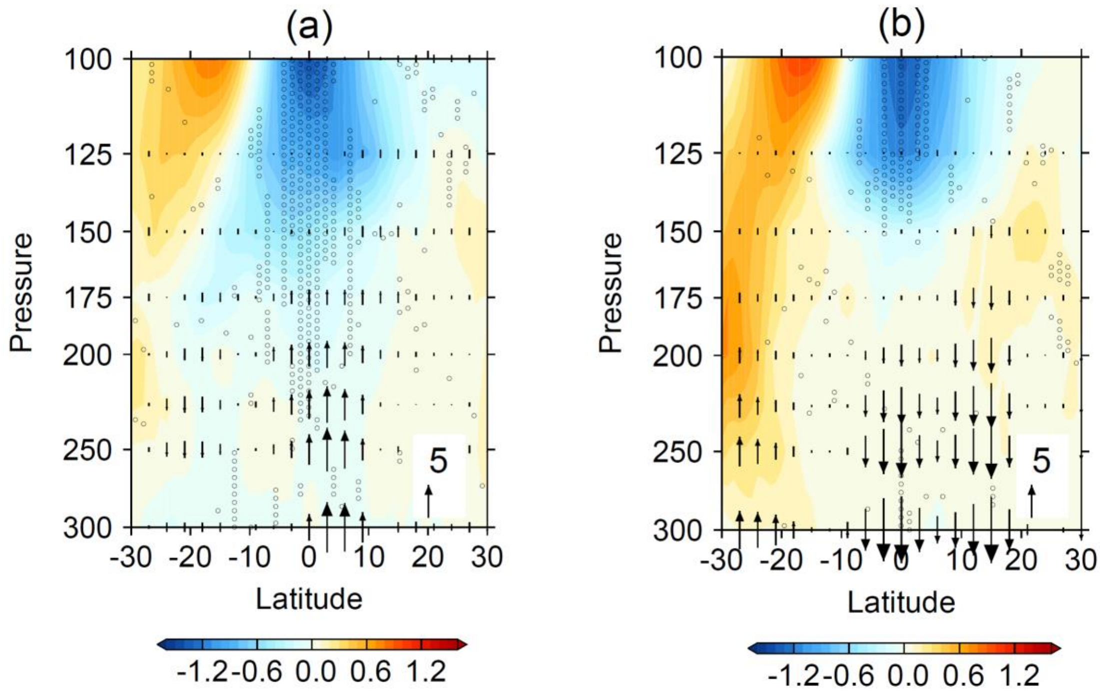


**Fig. 4** Difference in $\frac{\partial\theta}{\partial z}$ (filled color, unit: K m$^{-1}$) and ω (vectors, unit: 10$^{-3}$ Pa s$^{-1}$) between EQBO and WQBO at (a) 90°E and (b) 140°E. Differences in $\frac{\partial\theta}{\partial z}$ above the 95% confidence level under the Monte Carlo test are shown by empty dots.

**Tables**

| EQBO year | zonal wind | Standardized Index | box region TEJ | WQBO year | zonal wind | Standardized Index | box region TEJ |
|---|---|---|---|---|---|---|---|
| 1987 | -24.1 | -1.6 | -10.6 | 1988 | 10.2 | 0.9 | -13.1 |
| 1992 | -23.9 | -1.6 | -11.9 | 1990 | 9.4 | 0.9 | -16.5 |
| 1994 | -24.3 | -1.7 | -14.6 | 1993 | 9.0 | 0.8 | -10.6 |
| 1996 | -17.6 | -1.2 | -9.3 | 1995 | 10.8 | 1.0 | -9.7 |
| 1998 | -20.5 | -1.4 | -8.3 | 1997 | 13.1 | 1.1 | -13.8 |
| 2001 | -14.1 | -0.9 | -14.3 | 1999 | 9.5 | 0.9 | -15.5 |
| 2007 | -9.7 | -0.6 | -10.0 | 2000 | 13.1 | 1.1 | -12.7 |
| 2010 | -23.0 | -1.6 | -9.6 | 2002 | 8.8 | 0.8 | -15.0 |
| 2015 | -10.0 | -0.6 | -11.0 | 2004 | 9.8 | 0.9 | -16.6 |
| 2016 | -14.3 | -0.9 | -13.7 | 2006 | 9.1 | 0.8 | -13.3 |
| 2018 | -21.3 | -1.4 | -16.4 | 2008 | 8.3 | 0.8 | -10.0 |
| 2020 | -13.9 | -0.9 | -7.4 | 2009 | 9.3 | 0.8 | -15.6 |
| | | | | 2011 | 11.7 | 1.0 | -14.8 |
| | | | | 2013 | 7.6 | 0.7 | -13.8 |
| | | | | 2014 | 7.5 | 0.7 | -13.3 |
| | | | | 2017 | 11.8 | 1.0 | -13.8 |
| | | | | 2019 | 8.6 | 0.8 | -13.4 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| average | -18.1 | | -11.4 | average | 9.9 | | -13.6 |

**Table 1.** The summer mean zonal wind at 50 hPa (U50, unit: m/s), standardized U50 observed at the Singapore radiosonde station (1°N/104°E), and averaged TEJ zonal wind (unit: m/s) in the black box region in Figure 2 of EQBO and WQBO years.