Using reanalysis datasets, the warming of the tropical tropopause in 1999 and its evolution are investigated. It is found that there is a strong rate of increase in tropical cold-point tropopause temperature (CPTT) in June 1999, with negative CPTT anomalies before June (March-April-May) and large positive anomalies after June (July-August-September). Multiple linear regression analysis shows that deep convection, the quasi-biennial oscillation (QBO), and tropical upwelling associated with the Brewer-Dobson circulation (BDC) largely explain the variations of CPTT in 1999. Before June, enhanced deep convection resulting from increased sea surface temperature (SST) over the western Pacific and enhanced tropical upwelling of the BDC lead to a higher and colder tropopause. Those two factors explain 22% and 17% of the variance in CPTT, respectively. In June, the transformation of the east phase of QBO to the west phase contributes up to more than 50% of the variance in CPTT changes. After June, reduced tropical upwelling induced by weakened wave activity results in the warmer tropical tropopause temperatures to a large extent.

1. Introduction

Stratospheric processes can influence tropospheric weather and climate system not only through the dynamical processes [1–5] but also via the radiative effects of the greenhouse gases in the stratosphere [6, 7]. As one of the most important greenhouse gases in the stratosphere, water vapor plays a crucial role in the atmospheric radiation budget and chemical processes [8, 9]. The tropical tropopause temperature is the main factor controlling stratosphere water vapor variations [10–15]. That is, when air enters the stratosphere from the troposphere in the tropics, cold tropical tropopause would result in very low water vapor mixing ratios throughout the stratosphere by effective freeze-drying of the air [16, 17]. Dessler et al. [9, 18] demonstrated a close connection between interannual variations in tropical tropopause temperatures and stratospheric water vapor. A sudden decrease in the stratospheric water vapor after 2001 is attributed to the reduced tropical tropopause temperature [19]. Tian and Chipperfield [20] pointed out that a trend of +0.44 K/decade in tropical tropopause temperature can account for 70% of the modeled lower stratosphere water vapor trend. In addition, Rosenlof and Reid [12] showed that each degree of the tropical tropopause temperature cooling would lead to an approximately 15% decrease in saturated water vapor mixing ratios in the lower stratosphere. In addition to the importance of tropical tropopause temperature for stratospheric water vapor, changes in global atmospheric circulation associated with atmospheric angular momentum and the formation of tropical thin cirrus clouds are also strongly influenced by the tropical tropopause temperature [21–23].

The above analysis illustrates that the tropical tropopause temperature is significantly sensitive to climate variability and climate change, and therefore it has drawn a great deal of attention over the past decades [24–26]. Several studies have shown that changes in tropical tropopause temperature are the result of combined effects. Based on reanalyses of European Center for Medium-Range Weather Forecast
(ECMWF), Zhou et al. [27] analyzed the variability in the tropical cold-point tropopause temperature (CPTT) before 2000 using an empirical orthogonal function (EOF) analysis and showed that the leading modes of CPTT variability are associated with the quasi-biennial oscillation (QBO) and El Niño-Southern Oscillation (ENSO). Several studies have also confirmed that QBO and ENSO are the primary drivers of variations in tropical tropopause temperature from 1950 to 1980 [28–30]. Further observational evidence on ENSO or QBO-related CPTT changes are documented using the latest observational datasets [31, 32]. Apart from the effects of the QBO and ENSO, strong tropical convection can reach up to the tropopause and further lead to variations in the tropical cold-point tropopause height (CPTH) and CPTT [33, 34]. Zhou et al. [35] suggested that changes in tropical CPTHs are likely due to tropospheric convection to a large extent.

Except for their long-term trend and interannual variability [28, 35, 38–40], tropical tropopause temperature sometimes shows extreme warming or cooling in a year; for example, Randel et al. [19] found an abrupt decrease in tropical tropopause temperature (approximately −1 K) in 2001, leading to a sudden decrease of stratospheric water vapor during the same period. On the other side, the case associated with strong warming of the tropical tropopause deserves to be analyzed. In this study, we primarily focus on investigating the sudden warming of the tropical tropopause in 1999 and relevant factors or processes which influence the warming. The paper is organized as follows: Section 2 gives a description of the data and methods used in the study; the warming in 1999 and its relevant impact factors are analyzed in Sections 3 and 4. Conclusions are given in Section 5.

2. Data and Methods

The tropical CPTT is defined in this study as the position where the temperature is coldest in the temperature profile. The tropics extend from 20°N to 20°S. Zonal wind shear between 10°N and 10°S at 70 hPa, which is close to the tropopause, is used as an index for the stratospheric QBO [41].

To diagnose the effect of the BDC on the sudden warming, the vertical velocity of the BDC is calculated in this study [42].

$$\tilde{w} = \bar{w} + \frac{1}{r_0 \cos \phi} \frac{\partial}{\partial \phi} \left( \frac{v' \theta' \cos \phi}{\theta_p} \right),$$

where \(r_0\) is Earth’s radius, \(\theta\) is potential temperature, \(\phi\) is latitude, and \(w\) and \(v\) are the vertical and meridional velocity, respectively.

The effective number \((N_{eff})\) of degrees of freedom (DOF) [43] is used in this study, which can be determined by the following approximation [44]:

$$\frac{1}{N_{eff}} \approx 1 + \frac{2}{N} \sum_{j=1}^{N} N_{XX} (j) N_{YY} (j),$$

where \(N\) is the sample size and \(N_{XX}\) and \(N_{YY}\) are the autocorrelations of two sampled time series, \(X\) and \(Y\), at time lag \(j\), respectively.

The daily meteorological fields used in this study are obtained from the European Center for Medium-Range Weather Forecast Interim (ERA-Interim) reanalysis data for the time period between 1994 and 2005 (because we only investigate the tropopause temperature warming in 1999, the use of data extending from 1994 to 2005 is sufficient for this study). ERA-Interim reanalysis data assimilates model outputs and satellite observations and provides data at a horizontal resolution of 1.5° latitude \(\times\) 1.5° longitude on 37 vertical layers from 1000 to 1 hPa [45, 46]. More details about ERA-Interim reanalysis data can be found in Dee et al. [47].

The Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis dataset with a horizontal resolution of 1.5° latitude \(\times\) 1.5° longitude and GOZCARDS datasets. The CPTT from ERA-Interim is calculated as the daily values minus those of daily mean values for the period of 1994–2005.

3. The Strong Warming in the Tropical CPTT in 1999 and Its Associated Impact Factors

Figure 1(a) shows time series of CPTT for the period of 1994–2005 derived from the ERA-Interim, MERRA, and GOZCARDS datasets. The CPTT from ERA-Interim is consistent with that from the other two reanalyses. A noticeable feature of Figure 1(a) is the relatively large increase in CPTT in 1999 and this phenomenon is also reflected in the other two datasets. Note that the positive CPTT anomalies in 1999 are strongest during the period of 1994–2005. Figure 1(b) further shows the temporal evolution of daily tropical CPTT in 1999 and the daily CPTT climatology in the 2000s. Clear evidence of a large rate of increase in CPTT anomalies is found in June and the CPTT anomaly reaches its maximum until July and the anomaly persists to September. It is interesting that negative CPTT anomalies are found in March, April, and May. To further investigate the increase in CPTT, June of 1999 is labeled as the period of “warming,” March, April, and
May make up the “prewarming” period, and July, August, and September represent the “postwarming” period. Figures 2(a) and 2(b) show the spatial distribution of CPTT during the “prewarming and postwarming” periods. During the “prewarming” period, the tropical CPTT exhibits positive anomalies over central Pacific Ocean and negative anomalies over the western Pacific Ocean with a minimum of approximately \(-2.30 \text{ K}\). The large negative anomalies cause the tropical mean CPTT in March, April, and May to be lower than the climatological CPTT values in the 2000s (Figure 1(b)). During the “postwarming” period, positive CPTT anomalies appear over the entire extent of the tropical oceans. The largest positive CPTT anomalies are located over the central Pacific Ocean and have values of approximately 3.12 K. Figure 2(c) shows the difference of CPTT between the “postwarming” and “prewarming” periods. It can be seen that
there are evident positive anomalies over the entire tropical oceans, further indicating that CPTT is larger during the “prewarming” period than during the “postwarming” period.

As mentioned in Introduction, tropical deep convection, the QBO, ENSO, and the BDC all have an impact on changes in the tropical tropopause temperature [31, 32, 48, 49]. In general, deep convection can lift up the tropopause and cause reduced tropopause temperature via adiabatic cooling processes [29, 36, 50]. Thus, we first analyze the CPTT variations related to deep convection. Figure 3(a) shows the differences in OLR during the “prewarming” period relative to the “prewarming” period. Note that OLR has been shown to be a good indicator of deep convection in the tropics [27]. It can be seen that there is an evident region of positive anomalies over the tropical eastern Indian Ocean and the western Pacific Ocean. This indicates that deep convection over the eastern Indian Ocean and western Pacific Ocean is stronger during the “prewarming” period than during the “postwarming” period. Figure 3(b) displays time series of daily OLR averaged over the tropical eastern Indian Ocean and the western Pacific Ocean, and tropical CPTT during all three periods (“prewarming,” “warming,” and “postwarming”). Evident negative OLR anomalies appear during all three periods, indicating enhanced deep convection. During the “prewarming” period, the intensity of deep convection is stronger than those of the other two periods. Significant correlation coefficients during the “prewarming” period imply that enhanced deep convection is associated with colder tropopause temperature.

Figures 4(a)–4(d) further show longitude-pressure cross sections of vertical velocity anomalies and meridional distributions of OLR changes during the “prewarming and postwarming” periods. The positive (negative) vertical velocity anomalies exactly correspond to the negative (positive) OLR anomalies. That is, during the “prewarming” period, there are large positive vertical velocity anomalies in the upper troposphere over the tropical eastern Indian Ocean and the western Pacific Ocean, and the positive anomalies can extend to the lower stratosphere (Figure 4(a)). This corresponds to the large negative OLR anomalies (Figure 4(b)) which are associated with enhanced deep convection and a higher and colder tropopause. During the “postwarming” period, relatively small positive vertical velocity anomalies, accompanied by negative vertical velocity anomalies, exist over the tropical eastern Indian Ocean and the western Pacific Ocean. However, the vertical velocity anomalies only reach 150 hPa (Figure 4(c)). This corresponds to the relatively small OLR values (Figure 4(d)), which are associated with depressed deep convection and a lower and warmer tropopause. From the differences of vertical velocity and OLR anomalies between the “prewarming” and “postwarming” periods (Figures 4(e) and 4(f)), large positive anomalies exist over the tropical eastern Indian Ocean and the western Pacific Ocean, indicating that deep convection is stronger during the “prewarming” period compared to that during the “postwarming” period. A question naturally arises here as to which processes are mainly responsible for the differences in deep convection seen during the “prewarming and postwarming” periods.

Previous study has shown that there are close correlations between sea surface temperature (SST) and deep convection [51]. Figures 5(a) and 5(b) show the spatial distribution of SST during the “prewarming and postwarming” periods. Due to the occurrence of a La Niña event in 1999, the spatial pattern of SST anomalies is characterized by apparent positive anomalies and a stationary wave pattern known as the Matsuno–Gill pattern over the eastern Indian Ocean and western Pacific Ocean [52, 53]. Notably, SST is higher during the “prewarming” period than during the “postwarming” period over the tropical western Pacific Ocean and, particularly, over the northwestern Pacific Ocean. This feature can be clearly seen in the difference plot of SST between these two periods (Figure 5(c)). Zhang [51] pointed out that the frequency and strength of deep convection substantially increase with changes in SST from 26.5°C up to approximately 29.5–30°C. Subsequently, Lau et al. [54] further
confirmed the results of Zhang [51] and suggested that OLR drastically decreases increasing SST, when SST varies from 26.5°C to 29.5°C. The mean SSTs over the tropical western Pacific Ocean during the “prewarming and postwarming” periods are 28.6°C and 27.9°C, respectively. Hence, the SST warming pattern may be one of the main factors causing the enhanced deep convection during the “prewarming” period.

The zonal wind anomalies associated with the QBO could lead to anomalous meridional circulations [55, 56]. Anomalous westerly wind shear during the west phase of the QBO which descends from the upper stratosphere to the lower stratosphere induces an anomalous equatorward motion that leads to a warmer and lower tropopause in the tropics and vice versa for the east phase of the QBO [41]. Figure 6(a) shows the time series of CPTT variations and 70 hPa zonal wind anomalies averaged over the latitude bands (10°N–10°S). It can be seen that the east phase of the QBO during the “prewarming” period converts to the west phase of the QBO during the “postwarming” period. The correlation coefficients between the CPTT and the zonal wind variations are significant during the “warming” period, indicating that the QBO may be responsible for the strong warming of the tropical tropopause in 1999. To further investigate the effect of the QBO on the tropopause, Figures 6(b) and 6(c) show time-pressure cross sections of tropical averaged zonal wind and temperature variations, respectively. From Figure 6(b), we can identify a transition from the east phase of the QBO during the “prewarming” period to the west phase of the QBO during the “postwarming” period at tropopause layer, which leads to a transition from negative temperature anomalies to
positive temperature anomalies (Figure 6(c)). This process would represent a key influence on the warming of the tropopause. The QBO signal in the tropical tropopause is mainly characterized by zonally symmetric structure [27, 28], and the zonally symmetric pattern of CPTT anomalies shown in Figure 2(b) further confirms the effect of the QBO on CPTT.

Randel et al. [19] pointed out that the enhanced tropical upwelling associated with the BDC results in a colder tropical tropopause after 2001, indicating that the strength of the BDC
plays an important role in the variations of CPTT. Figure 7(a) shows the time series of CPTT and variations in the vertical velocity of the BDC over the tropical regions. It shows that the BDC is weakened during the "warming" period. During the "postwarming" period, the BDC is slightly strengthened compared with the period of "warming." During the "prewarming," "warming," and "postwarming" periods, the maximum correlation coefficients between the vertical velocity of the BDC and the CPTT can reach up to $-0.47$, $-0.72$, and $-0.62$ when the BDC leads the CPTT by 4 days, 3 days, and 13 days, respectively. The enhanced (weakened) tropical upwelling corresponds to cooler (warmer) CPTT. Figures 7(b) and 7(c) further show the map of correlation coefficients between the vertical velocity of the BDC and CPTT variations over the tropical regions during the "prewarming and postwarming" periods. The vertical velocity of the BDC is negatively correlated with the CPTT during these two periods. During the "prewarming" period, significant correlation coefficients are mostly located over the tropical eastern Pacific Ocean with the highest correlation coefficient being $-0.34$. During the "postwarming" period, significant correlation coefficients are found over the whole Pacific and Indian Oceans, especially over the tropical central and eastern Pacific, where the correlation coefficient can reach up to $-0.4$. Dhomse et al. [57] revealed that the strength of planetary wave activity in the stratosphere associated with the Eliassen-Palm flux (EP flux) is strongly correlated with the strength of the BDC. Figure 8 shows the patterns of the EP flux and the EP flux divergence during the "postwarming" period. Figures 8(a) and 8(b) are the climatology and the anomaly distributions associated with the EP flux, respectively. During the "postwarming" period, tropospheric planetary waves enter stratosphere in the Southern Hemisphere middle latitudes (Figure 8(a)). The downward EP flux anomalies and positive EP flux divergence anomalies in the southern middle latitudes of the stratosphere indicate that the planetary wave activity is weakened during this period (Figure 8(b)). This weakening of planetary wave activity is responsible for the abatement of the BDC [58] during the "postwarming" period.

4. The Contributions of Different Impact Factors to Tropopause Warming in 1999

The analysis above suggests that deep convection, the QBO, and upwelling associated with the BDC all contribute to the strong warming of the tropical tropopause in 1999. A multiple regression model (MLR) analysis is used to calculate...
the variance contributions of these factors to the variations in the CPTT. Note that the MLR analysis has been widely used to study the attribution of the observed variations [59]. The proxy variables applied here are OLR over the tropical western Pacific Ocean (olr), zonal mean wind at 70 hPa averaged over 10°N–10°S (u), and tropical upwelling velocity at 100 hPa averaged over 20°N–20°S (w_s). The MLR equation is as follows:

$$\text{cptt}(t) = b_0 + b_1 \text{olr} + b_2 u + b_3 w_s,$$

where $t$ is the day and $b_i$ is the regression coefficient associated with each factor.

Before establishing the regression model, it is necessary to investigate the correlation among these three regressors to check whether these three regressors are independent of each other. Table 1 lists the correlation coefficients among olr, u, and $w_s$ used in the MLR analysis during three periods ("prewarming," "warming," and "postwarming"). It shows that the deep convection, QBO, and BDC are uncorrelated at the 95% confidence level for each period. It implies that the three regressors are independent of each other.

Figure 9 shows the regressed and observed daily mean time series of CPTT variations in 1999. The high correlation coefficient ($r = 0.96$) between the regressed and observed CPTT variations indicates that the variations of deep convection, the QBO, and the upwelling associated with the BDC can explain the CPTT in 1999 well.
Table 2: Explained variances of deep convection, the QBO, and upwelling associated with the BDC during three periods in the regression model.

|                  | Prewarming | Warming  | Postwarming |
|------------------|------------|----------|-------------|
| Deep convection  | 22%        | 1%       | 4%          |
| QBO              | 0.7%       | 52%*     | 6%*         |
| Upwelling        | 17%*       | 3%       | 28%*        |

"*" denotes that the explained variances exceed the significance test at the 99% confidence level.

The explained variances of the three factors during three ("prewarming," "warming," and "postwarming") periods are listed in Table 2. We can see that the explained variances of the three factors are different during the three periods and the maximum variance contributor for each period is also different. During the "prewarming" period, deep convection and the BDC can account for 22% and 17% of explained variances of the CPTT variations, respectively. This implies that the enhanced deep convection and upwelling associated with the BDC contribute to the colder tropopause to a large extent. During the period of "warming," QBO explains 52% of the variance, indicating that east-west QBO phase transition largely contributes to the large warming rate of the CPTT in June 1999. During the "postwarming" period, the BDC contributes to 28% of the explained variance. This implies that the anomalous warming of the tropopause after a strong rate of increase in the CPTT in June 1999 is most likely attributed to the reduction of the BDC. The MLR analysis shows that QBO east-west phase transition is largely responsible for the large rate of increase in the CPTT in June 1999. One may wonder that QBO east-west phase transition is a regular phenomenon with ~2-year cycle; why does the CPTT show large rate of increase only in 1999? Figure 10 shows time-pressure cross sections of temperature and zonal wind from 1994 to 2005. There are evident QBO signals in both tropical zonal wind and temperature. To be specific, westerly shear in the zonal wind is associated with warm temperature anomalies and easterly shear is associated with cold anomalies. In the years 1995, 1997, 1999, 2002, and 2004, westerly winds gradually propagate downward from the upper stratosphere to the lower stratosphere with the east-west phase transition of the QBO at 70 hPa. Correspondingly, a warm anomaly propagates from the upper stratosphere to the lower stratosphere in these years. It is interesting that the warm temperature anomaly only descends to 70 hPa in 1995, 1997, 1999, 2002, and 2004, while the warm temperature anomaly in 1999 can reach the tropopause. This indicates that the downward propagation of the QBO signal from the upper stratosphere to the tropopause plays a critical role in the large rate of increase in the CPTT in 1999.

5. Conclusions

Using reanalysis datasets, the warming of the tropical tropopause (the relatively large increase in CPTT) in 1999 and its evolution are investigated. It is found that there is a strong rate of increase in the CPTT in June 1999 during the period of "warming." Negative CPTT anomalies occur before June (March-April-May) during the "prewarming" period, and large positive anomalies occur after June (July-August-September) during the "postwarming" period. It is further revealed that the variations of CPTT are closely related to deep convection, the QBO, and the tropical upwelling associated with the BDC. During the "prewarming" period, enhanced deep convection induced by an increase in SST over the western Pacific together with enhanced tropical upwelling of the BDC contributes to a higher and colder tropopause. The MLR analysis shows that the changes in deep convection and the tropical upwelling account for 22% and 17% of explained variances of the CPTT variations, respectively. During the period of "warming," the QBO evidently undergoes a transition from its east phase to its west phase. MLR analysis shows that this east-west phase transition in the QBO can contribute up to 50% of the explained variance in the large rate of increase in tropopause warming. During the "postwarming" period, weakening of the mean tropical upwelling of the BDC resulting from reduced wave activity in the southern middle latitudes of the stratosphere results in a warmer tropical tropopause that explains 28% of the variance in CPTT.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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