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INTERDECADAL VARIABILITY OF QUASI–BIENNIAL OSCILLATION OF STRATOSPHERIC ZONAL WIND

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Abstract: This study investigates the interdecadal variability of Quasi-biennial Oscillation (QBO) based on the sounding data in the stratosphere, ERA-40 and ERA-interim reanalysis data in the past 62 years. The QBO periodicity experiences a significant interdecadal variability; the longer (shorter) the mean period, the smaller (larger) the amplitude of variation is. The QBO amplitude varies in a cycle around 10 to 15 years and in an out-of-phase correlation with the period. In addition, there is an increasing trend of the QBO amplitude in 30 to 10 hPa, while a little declining trend in 70 to 40 hPa. The deviation of the QBO zonal wind extremum centers from the equator also shows interdecadal variability. The deviation location of the easterly core is generally in the reverse side to the westerly core, which means that when the easterly core is on one side of a hemisphere, the westerly core is on the other side.

Key words: statistical feature; QBO; interdecadal variability; zonal wind; asymmetric feature

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1 INTRODUCTION

The quasi-biennial oscillation (QBO) is a significant interannual variation in the tropical stratosphere, typically measured around 30 to 50 hPa. The zonal winds oscillate from easterly to westerly and propagate downward with a variable cycle averaging approximately 28 months (Baldwin et al. [1]). Although the stratospheric QBO is a tropical phenomenon, its phase and amplitude have impact on the circulation in a wide range area of the troposphere and stratosphere. For example, the transport of the aerosol generated by volcanic eruptions has been shown to depend on the phase of the QBO[1]. Studies have demonstrated that the stratospheric sudden warming is more likely to occur in the easterly phase of the QBO (Seol and Yamazaki[2]). The QBO also exerts influence on the precipitation and monsoon in Asia Pacific. For example, Inoue and Yamakawa found that there was more precipitation in the Philippines and more drought near Japan during the easterly phase of the QBO[3]. Seo et al. pointed out that in the QBO westerly phase, the spring rain belt extending from southeastern China to Japan tends to move southward[4]. Liang et al. revealed that the interannual variation of the South China Sea summer monsoon onset is negatively correlated with the zonal wind of the QBO at 30 hPa leading by about 18 months[5]. The QBO can also affect the monsoon activity by modulating El Niño-Southern Oscillation (ENSO) (Garfinkel and Hartmann[6]; Hatsushika and Yamazaki[7]). Chen et al. suggested that the QBO can affect the strength of polar vortex on an interannual scale by changing polar waveguides to influence winter circulation in East Asia[8-11]. During the QBO easterly phase, the wave activities were enhanced to lead to an anomalous warming in northeast Asia, a weakened East Asian trough and weakened circum-polar westerlies in mid-high latitudes in winter. These phenomena are expected to be caused by the indirect modulation of stratospheric circulation over mid-high latitudes and polar region by the QBO through wave-flow interaction. In addition, the QBO phase is associated with the frequency of tropical cyclones in the North Atlantic and the northwest Pacific (Gray[12]; Shapiro[13]; Chan[14]; Ho et al.[15] ; Camargo and Sobel[16]). During the QBO westerly phase, the tropical cyclones are more frequent in the North Atlantic and the northwest Pacific. While in the Indian Ocean, the tropical cyclone activity increases in the easterly phase. One explanation is that the oscillation of the QBO changes the vertical wind shear near the tropopause, which in turn has an impact on the tropical cyclone activity (Landsea and Gray[17]; Gray et al.[18]). The first pioneering observation and insight on the behavior of the QBO phenomenon came from Reed et al. through the sounding data obtained on the Canton Island during the 1950s and 1960s

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(Hastenrath[19]). Holton and Lindzen are the first to propose an explaination of the QBO based on vertically propagating waves in 1972[20]. The most widely accepted theory at present is that equatorially trapped Kelvin waves provide the westerly momentum and Rossby gravity waves provide easterly momentum to produce the QBO oscillation through a mechanism of wave-flow interaction.

Because the QBO is dominant on interannual variation and the time series of data is limited, there is little research on its interdecadal variation. Because of the influence of the QBO on the atmospheric phenomena such as monsoon and polar vortex, its interdecadal variation may also be expected to affect other atmospheric systems. Therefore, whether there exists any interdecadal variation of its period and amplitude, and what the behavior is like, these problems are worth to be discussed and analyzed. The purpose of this study is to analyze the interdecadal variability of the QBO period, amplitude, intensity and extremum center of the QBO via radiosonde data and reanalysis data, and reveal the main features of the QBO interdecadal variation.

2 DATA AND METHODOLOGY

The dataset used in this study includes: (1) monthly mean radiosonde data from stratosphere group at the Free University of Berlin (FUB), which contains stations near the equator from 1953 to 2014[21]; (2) monthly mean zonal wind data from ERA-40 (1957-2002) and ERA-interim (2002-2014) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Uppala[22]; Dee et al.[23]); (3) solar radiation at a wavelength of 10.7 cm provided by the Solar Monitoring Program operated by the National Research Council and Natural Resources Canada[24].

The radiosonde data provided by the FUB is composed of the data from three radiosonde stations near the equator: Canton Island, Gan/Maldives Islands and Singapore. Studies have shown that the zonal differences of the QBO are quite small, so this radiosonde data series is supposed to perform well about the features of the QBO (Marquardt and Naujokat[25]). Besides, we utilize the ERA-40 and ERA-interim data to compose a much long-time series grid data (1957-2014). By comparing the grid data and sounding data, there is not much difference between these two, especially after the 1970s. Taking data at 30 hPa as an example, before 1970, the correlation coefficient between ERA and FUB data is 0.95, and the standard deviation of the difference between these two datasets is 5.6 m/s. After 1970, the correlation coefficient is up to 0.99, and the standard deviation of the difference is 2.5 m/s. After 1979, the satellite data were added to the ERA reanalysis data by assimilation. Therefore, the ERA data were closer to the sounding data after the satellite data were added. For example, the standard deviation of the biases was 4.1 m/s from 1969 to 1978, but 2.9 m/s from 1979 to 1988. Above all, although there are some biases between FUB and ERA data before the 1970s, there is no significant difference, thus ERA grid data can be reliably used to examine the interdecadal variability of the QBO. Furthermore, Naujokat pointed out there are some uncertainties of the sounding data in early years due to the scarcity of observations[26].

In this study, wavelet analysis (Morlet complex wavelet) is applied to carry out periodicity analysis (Torrence and Compo[27]), and Butterworth band-pass filtering is used to filter data (Stephen[28]).

3 INTERDECADAL VARIABILITY OF PERIODICITY

The QBO is the most significant interannual signal in tropical stratosphere. The most remarkable feature of the QBO is the interannual oscillation of zonal wind and associated temperature. The wind regimes propagate slowly downward over time. Therefore, the period of the QBO is usually defined by the oscillation of zonal wind. The phase of zonal winds in different levels is not the same, so the definition of the QBO phase is somehow subjective. Besides, the transition from westerly to easterly is often delayed between 30 and 50 hPa. Therefore, it is common to define the transition from easterly to westerly at a certain level as the start node for calculating the QBO period. The solid line in Fig. 1a presents the time evolution of the QBO period based on the 30 hPa zonal wind (FUB sounding data), and the beginning of the period is defined as the transfer from easterly to westerly. The period at 40 hPa or 50 hPa is nearly the same as that at 30 hPa with a mean of approximately 28 months. Since the sounding data started from the easterly phase, thus the initial time of the period is 1953, but a complete QBO period started from 1956.

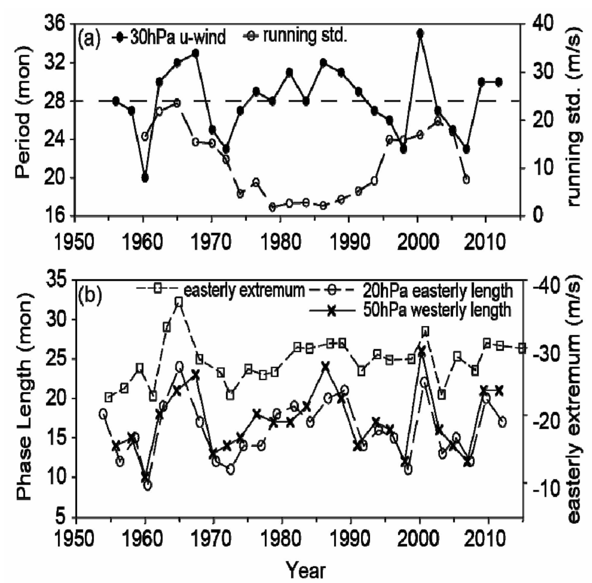

Figure 1. Time evolution of the duration of period (solid line) and its five-point running standard deviation (dotted line) at 30 hPa (units: month) (a). Time evolution of the easterly extremum (units: m/s), the duration of the easterly at 20 hPa and duration of westerly at 50 hPa (units: month) (b).

The dashed line in Fig. 1a shows the five-point moving standard deviation of the period, which reflects the magnitude of the period variation with time. According to the moving standard deviation curve, the interdecadal variation of the period can be divided into three stages: 1) a stage with large period variation from 1956 to 1973; 2) a stage with a small period variation from 1974 to 1994, accompanied with a moving standard deviation less than 7 months; 3) after 1994, it switched to a stage with great variation again. In addition to the differences in period variation, the duration of period presents corresponding changes in these three stages. The average period in 1956 to 1973 is 27.3 months, which is shorter than the long term mean of 28 months. The average period in 1974 to 1994 is 29.1 months, longer than the mean by 1.1 months. After 1994, the average period of the third stage is 27.4 months, also shorter than the long term mean value. Therefore, in the second stage, the length of period is large, but the period variation is small; while in the other two periods, the length of period is small, but the period variation is large.

Gruzdev and Bezverkhny mentioned that the QBO experiences two major cycles of 24 and 30 months, and their analysis found that the 30-month period dominated from 1976 to 1991[29]. Furthermore, Gabis and Troshichev examined the QBO cycle based on the changes in height profile of the zonal winds, and suggested that the QBO exists in three dominant periods of 24, 30 and 36 months[30]. They found out that the main reason for the diversion of period is related to the delay of transition between westerly and easterly and the delay is of seasonal dependence. According to the study of Gabis and Troshichev[30], the proportion of the 30-month cycles rose and the frequency of the 24-month cycles dropped contrarily during 1970 to1980, compared with that in 1950 to 1960. Since the 1990s, the percentage of 30-month cycles has been dropping again. The phenomenon of the interdecadal shifts in the period mentioned by Gabis and Troshichev[30] is similar to the results in our research.

The duration of easterly experiences a most notable variation in the layer of 10 to 20 hPa, while the duration of westerly varies most notably in the layer of 40 to 50 hPa. From the height-time evolution profile (figure not shown), it can be noted that the variation of duration mainly occurs during the easterlies propagating downward from the upper layer to the lower layer, corresponding with the easterly located in the layer of 10 to 30 hPa, and meanwhile, the westerly in the layer of 30 to 70 hPa. In some down-propagating processes, the easterly is lingering in the upper layer and the westerly sustains around the stratospheric bottom layer, resulting in a delay and prolongation of the duration.

An interesting phenomenon is that there exists a significant correlation between the magnitude of easterly extremum (square marks in Fig. 1b) and the duration of the upper-level easterly. For example, the correlation coefficient between the easterly duration at 20 hPa (circle marks in Fig. 1b) and the easterly extremum reaches −0.79, which means that the longer the easterly duration, the greater the easterly extremum is. There is also a significant correlation between the durations of the easterly at 20 hPa and the westerly at 50 hPa (cross marks in Fig. 1b) with a correlation coefficient of 0.85. This distinct correlation between the durations of the easterly and the westerly is supposed to represent the feature of propagation delay. In addition, the correlation between the duration of westerly winds at 50 hPa and the easterly extremum can also reach −0.60. All of these three correlations are significant at a confidence level of 99%. However, the westerly extremum does not have such a correlation with the durations of the easterly and the westerly.

4 INTERDECADAL VARIABILITY OF AMPLITUDE

According to the previous analysis, the QBO period is about 20 to 36 months. In order to further verify the above results, wavelet analysis is applied to figure out the periods in sounding data at 30 hPa and 50 hPa (Fig. 2). The dominant periods obtained by wavelet analysis are consistent with the aforementioned results. At 30 hPa and 50 hPa, the periods within 20.2 to 36.0 months pass a confidence level of 95%. Then, according to the QBO period, a procedure of band-pass filter is applied to filter the signal around 19 to 38 months, and Fig. 3a exhibits the filtered zonal wind at 50 hPa. The amplitude of zonal wind experiences an obvious interdecadal variation. In order to quantitatively measure the amplitude, wavelet analysis is performed on the filtered data to obtain the average power around 20 to 36 months (dashed line in Fig. 3b), which can well reflect the amplitude evolution of zonal wind. Due to the boundary error on both margins of

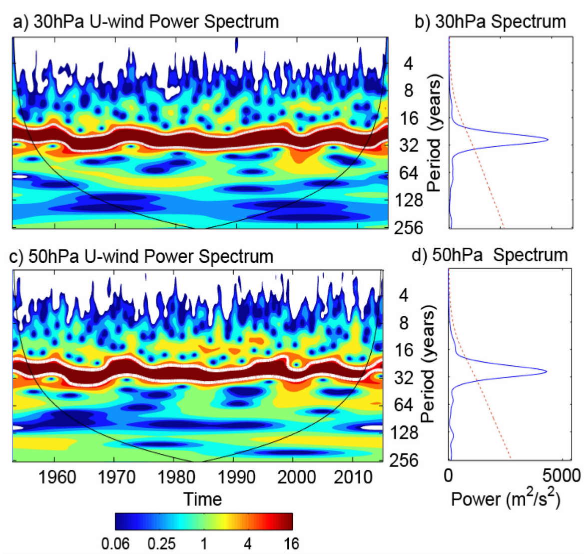

Figure 2. Wavelet analysis of zonal wind at 30 hPa (a) and 50 hPa (c) and the corresponding global spectrum (b, d). The white contours in (a, c) and the red lines in (b, d) are the 0.05 significance level lines.

the power-time series in wavelet analysis, only the data from 1956 to 2011 is extracted for analysis. By counting the time interval between adjacent peaks, we can determine that the interdecadal variation of amplitude is on a time-scale of about 10 to 15 years. The solid line in Fig. 3b is the time series of periods obtained by the corresponding maximum power points in the wavelet analysis. Compared with the periods obtained in section 3 (Fig. 1a) the wavelet-derived periods are more moderate in the extreme value regime because of the continuity of wavelet analysis. However, the period trends obtained by these two analysis methods are consistent to each other. By comparing the two curves in Fig. 3b, a remarkable negative correlation is clearly observed between the period and the amplitude intensity with a correlation coefficient reaching −0.58, indicating a longer period corresponding to a smaller amplitude.

Salby and Callaghan analyzed the sounding data in 1955 to 1996 and found that the amplitude of the QBO is positively correlated with the solar radiation, while the amplitude and the period of the QBO are in a negative correlation[31]. By comparing the amplitude power (dashed line in Fig. 3b) with the 10.7 cm solar radiation flux (Fig. 3c), it is observed that there is a significant positive correlation between amplitude and solar radiation of 0.51 in 1956 to 1986. However, after the 1990s, the correlation is inverse, presenting a correlation coefficient of −0.65.

From the aforementioned results in this study, a negative correlation between the amplitude and the period of the QBO does exist. However, the relationship between the QBO and the solar activity is not stable, and the correlation between the QBO and the solar radiation is inconsistent for different stages, indicating an unclear relationship between them. Hamilton, Fischer and Tung are also suspicious of the relationship between the QBO and the solar activity [32, 33].

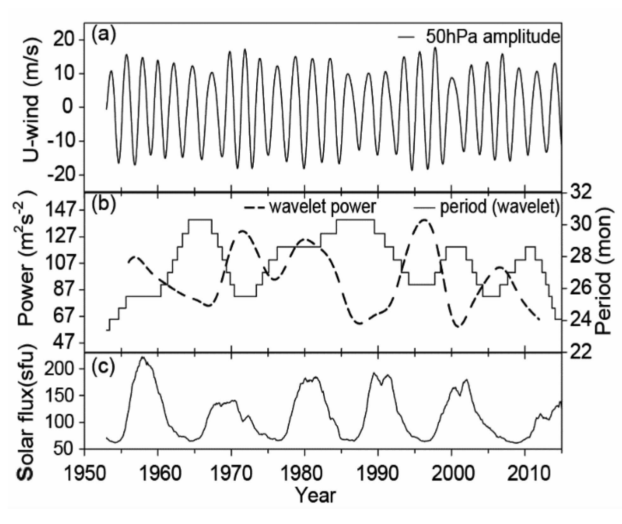

Figure 3. (a) Time series of 50 hPa zonal wind filtered in 19 to 38 months (units: m/s). (b) Time series of mean power of zonal wind in 20 to 36 months at 50 hPa obtained by wavelet analysis (dashed line, units: m^2/s^2) and the maximum power corresponding to the wavelet analysis (solid line, units: month). (c) 10.7 cm solar radiation (units: solar flux units).

To examine the interdecadal variation of amplitude at all levels, the amplitudes of the QBO in 10 to 70 hPa are analyzed in terms of the average power around 20 to 36 months in wavelet analysis, as shown in Fig. 4 (only partial levels plotted). It is exhibited that the amplitude in the upper levels (10 to 30 hPa) tends to increase with a noticeable trend, especially from 1956 to 1995. Meanwhile, the amplitude in 40 to 70 hPa levels tends to decrease, but the trend is relatively small. Based on the interdecadal oscillation of amplitude at all levels, the interdecadal characteristics of each level are slightly different, but similar on the whole. In 1975 to 1990, the oscillation at 15 hPa differs greatly from those levels below it, with a shorter period of oscillation in this stage. In the middle and lower levels, the interdecadal oscillation is consistent with the above analysis, in a period of about 10 to 15 years.

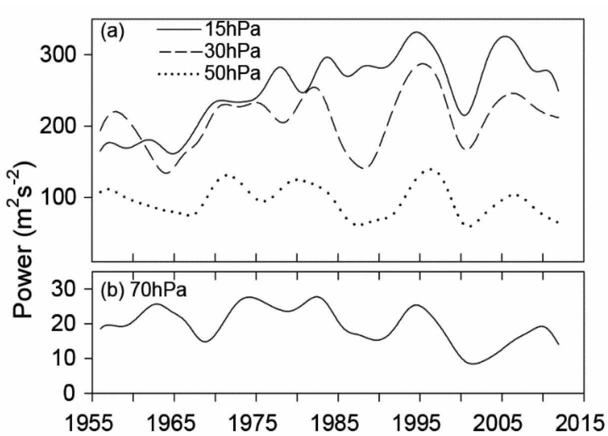

Figure 4. Average power of 20 to 36 months obtained by wavelet analysis in zonal wind at (a) 15 hPa, 30 hPa, 50 hPa and (b) 70 hPa, respectively (units: m^2/s^2).

5 INTERDECADAL FEATURES OF THE QBO ASYMMETRY TO THE EQUATOR

The QBO is generally symmetrical to the equator, and its asymmetry to the equator is mainly modulated by the seasonal evolution. Based on the ERA reanalysis data, it is found that the both westerly core and easterly core are more prone to the Northern Hemisphere (NH) in boreal winter but to the Southern Hemisphere (SH) in boreal summer (Fig. 6a). However, apart from the seasonal dependence, is there any interdecadal change in the meridional position of the QBO easterly and westerly extreme centers? This is worth our further analysis. To understand its interdecadal offset from the equator, the ERA data is applied by removing the seasonal variations, as example shown in Fig. 5a (only the profile in 1961 to 1974 is plotted). Then, the ERA reanalysis data is decomposed to two components to identify the meridional offset from the equator: the equatorial symmetric component $Us=(U(y)+U(-y))/2$ and the antisymmetric component $Ua=U(y)-Us$. The antisymmetric component is supposed to represent the deviation signal from the equator. The symmetric and antisymmetric field profiles are shown in Fig. 5b and Fig. 5c, respectively. It can be identified from Fig. 5 that the extremum of the westerly core is deviated to the NH in the late 1963 and deviated to the SH in the late 1969. The antisymmetric field processed in a way mentioned above is anti-symmetric about the equator, so the signal in the NH can fully represent the asymmetry situation. Examining the standard deviation variation of the antisymmetric component with latitude in Fig. 6b, a maximum value is observed at 10°N and in the levels of 20 to 50 hPa, which means that the maximum variation occurs at 10°N. In the levels above 20 hPa, the standard deviation increases with latitude, indicating that the asymmetric feature at higher levels is expected to be modulated by other factors in high latitudes. The antisymmetric component of zonal wind at (10° N, 30 hPa) is shown in Fig. 6c. There exists an obvious interdecadal variability in the five-year moving average data series (thick solid curve in Fig. 6c). In the stage of 1957 to 1973, the easterly anomaly was dominant in the NH, and it shifted to westerly anomaly from 1973 to 1995. Then, in 1995 to 2007, it shifted back to easterly. And it turned to westerly anomaly again after 2007. These anomalies of the zonal winds in the antisymmetric field actually reflect the deviation of the QBO from the equator. For example, the westerly anomalies in 1973 to 1995 actually represent that the westerly core is offset to the north side of the equator, while the easterly core is offset to the south side of the equator (Fig. 6c).

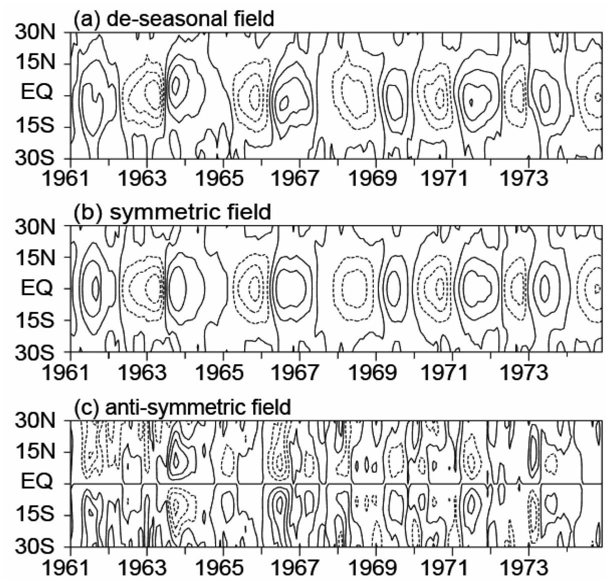

Figure 5. Time evolution of zonal wind by removing seasonal cycle (a), symmetric component (b), antisymmetric component (units: m/s) (c). Interval in (a, b) is 8 m/s and interval in (c) is 2 m/s; solid line is positive value, dashed line is negative value.

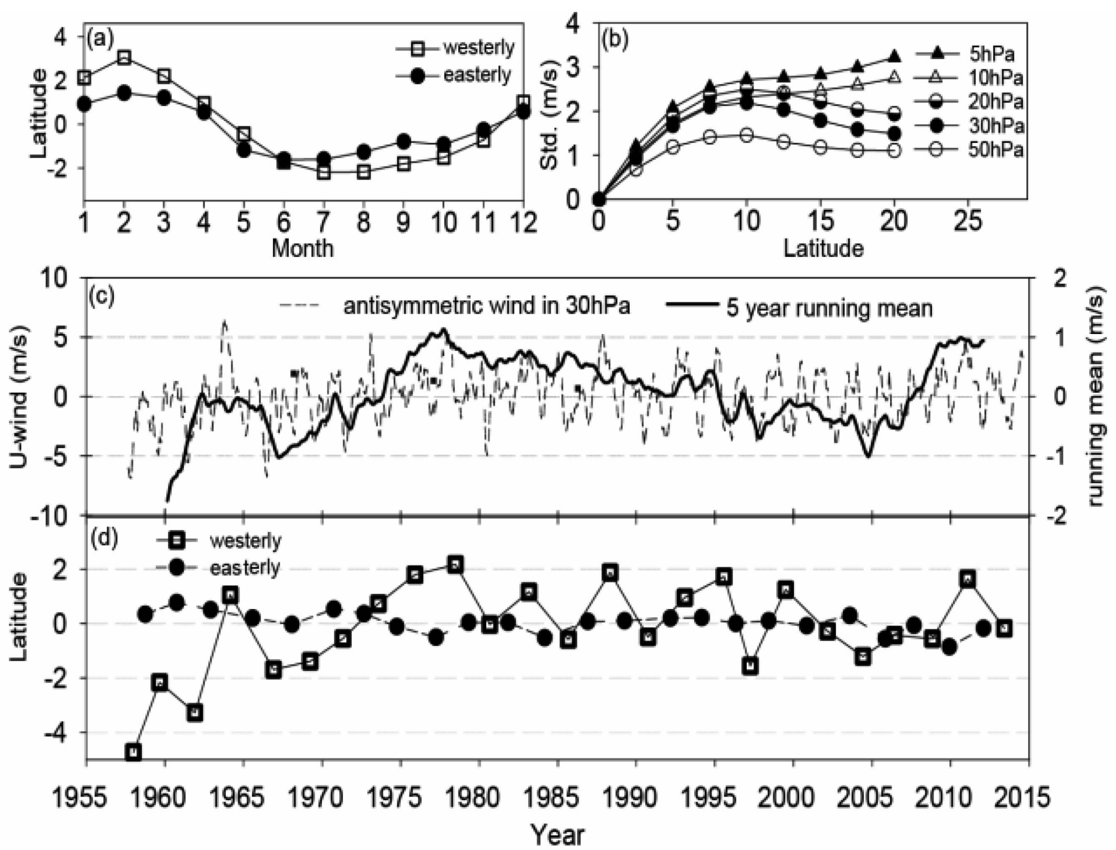

Figure 6. The average latitude of westerly (hollow square) and easterly (solid square) centers in each month (a). Standard deviation of antisymmetric field in 50 to 5 hPa over different latitudes (units: m/s) (b). Time series of the antisymmetric wind (dotted line) at (10°N, 30 hPa) and its five-year running mean (solid line) (units: m/s) (c). Average latitude of westerly (hollow square) and easterly (solid circle) centers within 70 to 10 hPa in each period (d).

Furthermore, the antisymmetric component reveals a remarkable periodicity. By analyzing the antisymmetric wind field, it can be identified that there is a significant and consistent period of 21 months in layer 20 to 50 hPa. And in higher levels, there is a period of roughly 8 months. Taking the data at (10°N, 20 hPa) as an example, its wavelet analysis is presented in Fig. 7. The global power spectrum in Fig. 7b exhibits that there are two peaks passing the 95% confidence level. One peak is at 20.8 months, which is the most significant peak, the other peak is at 8.3 months. As discussed above, these two periods is not within the dominant QBO period range. Actually, the 21-month and 8-month periods result from the non-linear interaction between the QBO period and the annual cycle. The 21-month signal was first identified by Tung and Yang in 1994 through a spectral analysis of O_3[34]. And then it is confirmed by Hamilton using the antisymmetric method to separate the QBO and the non-linear signal of annual cycle[35]. The beat periods produced by the interaction between the QBO and the annual cycle can be explained by the following formula:

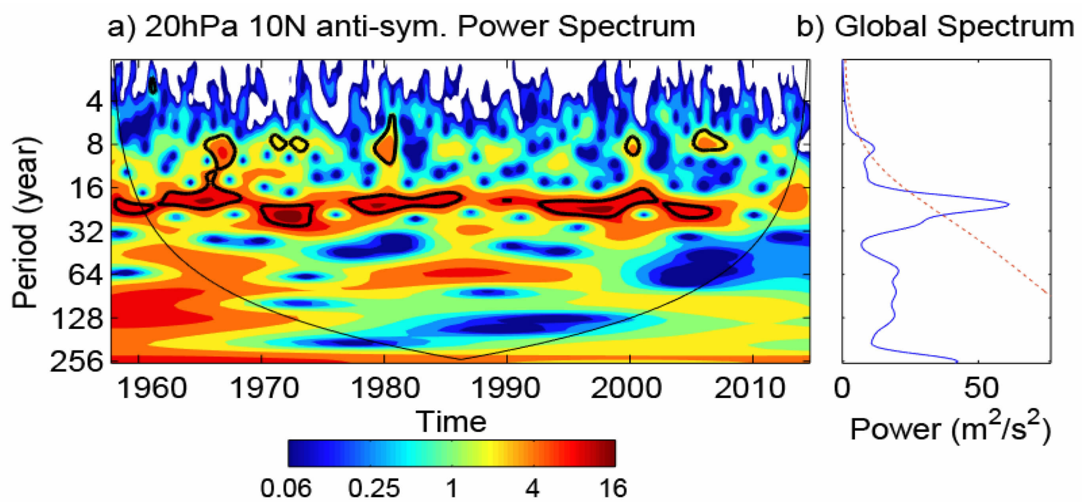

Figure 7. Wavelet analysis of antisymmetric zonal wind at (10°N, 20 hPa) (a) and its global power spectrum (b). Bold black contour in (a) and red line in (b) note the 0.05 significance level.

$$\sin(2\pi t/28)\times\sin(2\pi t/12)=1/2\times[\cos(2\pi t/21)-\cos(2\pi t/8.4)] \quad (1)$$

There is an inconvenience in the antisymmetric field analysis, because it cannot figure out whether the offset is caused by the westerly or easterly core. Taking the westerly anomaly of asymmetric field for example, it is possible either the westerly core deviates to the NH, or the easterly core deviates to the SH from the equator. In this case, the fact should be examined with the aid of the QBO phase itself. In order to identify the deviation of the westerly and easterly cores from the equator, respectively, after removing the seasonal variation, the easterly and westerly cores are obtained by marking the latitude and altitude between 70 to 10 hPa and then extracting the center between 70 to 10 hPa and calculating the average latitude in each descending process. After that, we obtain the latitude-time series of westerly and easterly cores. The time series are shown in Fig. 6d. The deviation of the westerly core (square marks in Fig. 6d) is generally consistent with that of the antisymmetric component (Fig. 6c), while the easterly core is deviated much less from the equator compared with the westerly core. It means that the asymmetry is more pronounced in the QBO westerly phase. This phenomenon can also be verified with the variation intensity of the antisymmetric component by examining the westerly and the easterly, respectively. The standard deviation of the asymmetry component at (10°N, 30 hPa) is 2.7 m/s in the westerly phase, and only 1.6 m/s in the easterly phase. It can also be observed in Fig. 6d that the offset direction of the easterly is generally opposite to the westerly core. That is, when the center of the easterly is in a certain hemisphere, the corresponding center of the westerly is in the other hemisphere. Therefore, the physical meaning of antisymmetric field discussed above is consistent with the offset of the zonal wind core.

The drift of extreme centers of the QBO can be explained by the meridional distribution of the temperature field. The thermal wind balance near the equator is as follows (Andrews et al.[36]):

$$\frac{\partial u}{\partial z}\cong-\frac{g}{\beta T}\frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right) \text{ or } -\frac{\partial u}{\partial p}\cong-\frac{R}{\beta P}\frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right) \quad (2)$$

From the above formula, the meridional deviation of zonal wind core is related to the non-uniform meridional gradient distribution in temperature. The effect of thermal anomaly on the drift of zonal wind center will be illustrated by an example in the following. In the antisymmetric field in Fig. 6c, there is a significant drift point around 1963 to 1964, presenting a sudden increase of the westerly anomaly in the NH. This abrupt point can be identified in Fig. 6d on the westerly core near 1964, and the abnormal duration of the period in Fig. 1b. According to previous studies, such a mutation is expected to be related to the volcanic activity of Mt. Agung in Indonesia in 1963 to 1964. Free and Lanzante have explored the association between volcanic eruptions and stratospheric temperatures and found significant warm anomalies in the lower stratosphere over the SH since the volcanic eruption of Mt. Agung (from February 1963 to 1964)[37]. Meanwhile, the warm center is in the lower and middle stratosphere near the equator (contours in Fig. 8a). Considering the upper stratospheric pressure is much lower than the lower level, thus the magnitudes of thermal wind are far greater in upper levels than in lower levels based on formula (2), which is not conducive to the analysis in this study. Therefore, we define the thermal wind as $U_T = -p\times(\partial u/\partial p)$, in which the pressure is added as a weight function compared with formula (2). For example, the thermal wind U_T in the layer of 10 hPa means the variation of zonal wind when the pressure decreases 10 hPa. According to this definition, the thermal wind U_T anomalies are shown in Fig. 8a (shading). Based on the temperature anomalies in Fig. 8a (contours), it can be noticed that due to the warm anomalies in the SH, the meridional temperature gradient in the SH is smaller than that in the NH, thus the thermal wind is stronger in the NH. Comparing with the zonal wind anomalies in Fig. 8b, we notice that a maximum center of the westerly anomaly is located near (7.5°N, 30 hPa). The latitude of the westerly center corresponds exactly to the latitude with the maximum thermal winds. And the

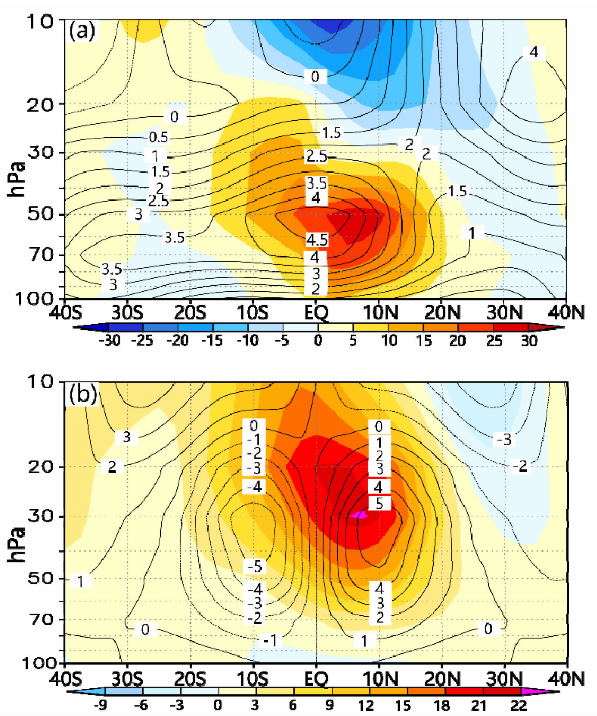

Figure 8. Temperature anomalies (contours, units: K) in December 1963 and the corresponding thermal wind anomalies (shading, units: m/s) (a). Zonal wind anomalies (shading) and antisymmetric zonal wind (contours) in December 1963 (units: m/s) (b).

altitude of the center corresponds to the transition boundary between the positive and negative thermal winds, which demonstrates that the wind and the temperature field in the tropical stratosphere can well satisfy the thermal wind balance. In addition, the antisymmetric component given in Fig. 8b (contours) also clearly presents the meridional deviation of the QBO center. It can be noticed that a positive center is located in 70 to 20 hPa over 10° N in the antisymmetric field, indicating the zonal wind center moving northward from the equator.

6 SUMMARY AND DISCUSSION

In this study, the evolution features of zonal wind in the stratosphere have been examined to explore the interdecadal characteristics of the QBO over the past 62 years. The main results obtained in this study are summarized as follows:

(1) There exists interdecadal variation in the QBO period. The longer (shorter) cycles are characterized with a smaller (larger) variation in the length of period.

(2) There are differences in the trend of the QBO amplitude in different levels. There exists an increasing trend in 10 to 30 hPa from 1950 to 1995, while a slight decreasing trend in 40 to 50 hPa.

(3) The QBO amplitude experiences an interdecadal variability in a cycle of around 10 to 15 years. There is a significant out-of-phase correlation between the QBO amplitude and the duration of the QBO cycle. And there is no significant relationship between the QBO amplitude and the solar radiation.

(4) The phenomenon of the QBO center deviating from the equator exhibits obvious interdecadal variability. By analyzing the antisymmetric component in the NH, it is noticed that the easterly anomalies prevailed in 1957 to 1973 and in 1995 to 2007, and the westerly anomalies in 1973 to 1995 and in 2007 to 2014. On the trend evolution, there is a tendency of westerly increase before 1977, and then it tends to be easterly in 1977 to 2007. After 2007, the westerly anomalies increase. The meridional offset of the westerly core from the equator is greater than that of the easterly core.

Based on the above analysis, it has been identified that the QBO experiences interdecadal variations in the period, amplitude and meridional deviation from the equator. However, the reasons for these interdecadal variations and their effects on other systems in the atmosphere are still not well understood and expected to be further explored. At present, there is not much discussion and exploration on the interdecadal variations of the QBO and the related mechanisms. Previous studies mainly focus on the correlation between the QBO and ozone or high-latitude systems, and are short of investigation of its own dynamic and thermodynamic aspects on interdecadal scale.

In this study, we only utilize the zonal wind data to discuss the interdecadal variations, and the thermodynamic characteristics in the QBO have not been discussed. Therefore, some QBO features revealed in this study can be further explored, such as its dynamic and thermodynamic features.

In addition, the correlation among the interdecadal variations of the period, amplitude and meridional deviation discussed in this study needs to be further explored. These three interdecadal variations have their own characteristics, but they are also related to each other. For example, there is a negative correlation between the amplitude and the period, and both the length of period and the deviation distance from the equator have a mutation point in the early 1970s. In addition, more details of interdecadal features are supposed to need further examination and discussion.

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