Decadal Amplitude Modulations of the Stratospheric Quasi-biennial Oscillation

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Abstract

Decadal variations of the quasi-biennial oscillation (QBO) in the equatorial stratosphere are investigated, using the Singapore data and reanalysis data from the 1950s to 2019/2020. It is found that the QBO is decadally modulated in the amplitude as well as in the period. These two decadal variations are negatively correlated with each other after the 1980s, while they show approximately positive correlations before the 1980s. In the time series of the QBO amplitude from the 1950s to 2014, there are four maxima (QBO\textsubscript{max}) around 1967, 1983, 1995, and 2005, and three minima (QBO\textsubscript{min}) around 1973, 1988, and 2000. Composite analyses of QBO\textsubscript{max} and QBO\textsubscript{min} based on these extrema reveal that the decadal amplitude variations have a maximum amplitude of about 3 m s\textsuperscript{−1} at 20 hPa in the vertical structure. In the horizontal structure, off-equator extrema of about 3.5 m s\textsuperscript{−1} appear around 5°N at 20 hPa, while extrema of about 1.8 m s\textsuperscript{−1} are situated around 5°S at 50 hPa. The decadal amplitude variations of the QBO are closely and positively correlated with the decadal components of Niño 3.4 sea surface temperature anomalies (SSTA) and the Pacific Decadal Oscillation index, suggesting that the tropical SSTA in the Central Pacific substantially influences the QBO in the decadal timescales.

Keywords quasi-biennial oscillation; decadal modulation; Niño 3.4; Pacific Decadal Oscillation

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1. Introduction

In the equatorial stratosphere, the zonal wind reverses direction with about a 28–month period, slightly longer than 2 years. This quasi-biennial oscillation (QBO) of wind is one of the dominant variabilities in the tropics and its effect extends to the extratropics in the stratosphere (e.g., Baldwin et al. 2001) through the modulation of the planetary wave propagation (e.g., Holton and Tan 1982; Naoe and Shibata 2010; Inoue et al. 2011; Lu et al. 2014). The basic mechanism of the QBO is explained by internal interactions between the mean flow and the waves propagating from the troposphere (Lindzen and Holton 1968; Holton and Lindzen 1972; Plumb and McEwan 1978).

The QBO period has a broad spectrum width from about 20 months to 40 months centered at about 28 months and much longer decadal components. Quiroz (1981) showed, using the Balboa radiosonde data (9.0°N, 79.6°W) from 1951 to 1979, that the QBO period was systematically modulated approximately and inversely in accordance with solar activity (11-year sunspot or solar cycle). Salby and Callaghan (2000) demonstrated more distinctly a close connection between the solar cycle and the QBO, using longer combined radiosonde data, compiled by the Free University of Berlin (FUB), near the equator at three stations: Canton Island (2.8°S, 171.7°W); Gan, Maldives (0.7°S, 73.1°E); and Singapore (1.4°N, 103.9°E), from 1956 to 1996. They found that the duration of the QBO westerly phase at 45 hPa varies broadly from 10 months to 23 months, being longer during the solar minimum and shorter during the solar maximum.
On the other hand, the duration of the QBO easterly phase at that level sharply peaked near 12 months. In addition, Salby and Callaghan (2000) demonstrated a systematic modulation in the power of the QBO wind, which is approximately in-phase with the solar radio flux at 10.7 cm wavelength (F10.7).

In spite of the reference to the modulation of the QBO power by Salby and Callaghan (2000), another point of interest is the variation in the QBO period. Hamilton (2002), while examining a longer time series within the FUB data from 1953 to 2001, reconstructed a similar analysis of the Balboa data, which were originally reported by Wallace (1973). Hamilton (2002) found that although the correlation coefficient between the solar radio flux and the westerly duration is −0.46 over the 17 westerly phases during the 1956–1996 period investigated by Salby and Callaghan (2000), the correlation coefficient decreases to an insignificant −0.10 when computed over the 22 westerly phases in the longer record. He concluded that the strong apparent correlation between the QBO period and the solar cycle cannot be decisively ruled out but may hold only for a part of the full record. Hamilton and Hsieh (2002), applying the nonlinear principal component analysis to the FUB data from 1956 to 2000, asserted that the time series of the QBO period, objectively determined from the QBO phase based on multilevel data, does not show any clear connection with the solar cycle.

Pascoe et al. (2005), using ECMWF (European Centre for Medium-Range Weather Forecasts) Reanalysis (ERA-40) (Uppala et al. 2005) from 1958 to 2001 and ECMWF operational data from 2002 to 2004, examined the duration of westerly and easterly equatorial zonal winds at 44 hPa and observed an approximate 10-year periodicity in the duration of the QBO westerly phase, which is generally out of phase with the solar cycle. Fischer and Tung (2008), using the FUB data from 1953 to 2007, which spans five (200-year and 400-year) simulations of a 2.5-dimensional chemical–radiative–dynamical model and concluded that the main variability of the QBO period is based on an intrinsic property of the QBO itself, that is, “quantum” jumps of about 6 months between QBO periods occur in an apparently random fashion even without the solar cycle.

A possible reason for the anticorrelation and correlation between the QBO period and the solar activity may come from the interference of volcanic aerosols in the stratosphere because of the huge eruptions in the tropics, Mount Agung (1963), El Chichón (1982), and Mount Pinatubo (1991), the radiative heating of which could affect the downward propagation of the QBO (Salby and Callaghan 2000; Hamilton 2002; Fischer and Tung 2008). To clarify this mechanism, a longer data record without volcanic aerosols would be needed to remove possible volcanic influence (Fischer and Tung 2008; Kuai et al. 2009). However, the effects attributable to the volcanic eruptions should be largely confined to the first few years after each eruption (Hamilton 2002).

The variations in the QBO are also influenced by variations in the troposphere and in the sea surface temperature (SST). The effect of the Southern Oscillation on the QBO was suggested through an investigation of the anomalies of the northern polar vortex at 50 hPa (van Loon and Labitzke 1987). Maruyama and Tsumoku (1988), using the tropical three-station (Canton, Gan, and Singapore) data, demonstrated that El Niño in 1987 enhances the rate of QBO westerly descent, that is, the shorter duration of the easterly phase of the QBO. Yasunari (1989), from the analysis of three-station (Singapore, Koror, and Ponape) data in the equatorial Pacific, suggested that there is a coupling between the stratospheric QBO and the tropospheric QBO in the tropical lower altitudes (700 hPa and 850 hPa), the latter of which is also coupled with the SST anomalies (SSTa) beneath. Read and Castrejón-Pita (2012), analyzing ERA-40 and ERA-Interim (Dee et al. 2011) over ~50 years, presented that the stratospheric and tropospheric QBOs are weakly coupled but frequently lose mutual coherence. [Note that the tropospheric QBO is rather prevalingly referred to as the tropospheric biennial oscillation (TBO) (e.g., Meehl 1997; Chang and Li 2000).] On the other hand, some studies indicated that the stratospheric QBO and tropical TBO are not related (e.g., Barnett 1991; Xu 1992).

Geller et al. (1997) demonstrated through onedimensional model experiments that the variations in the momentum fluxes forcing the QBO are related to SST variations and are rectified into longer time variations of the QBO period. Taguchi (2010), using
the Singapore data, proved that the phase of the QBO propagates faster during El Niño than during La Niña, and the amplitude of the QBO is smaller during El Niño. Huang et al. (2012), using reanalysis data and the Singapore data, presented significant correlations between the QBO and tropical SSTa in the Pacific, that is, Niño 3.4 (5°S–5°N, 120°–170°W), over the timescale of the El Niño-southern oscillation (ENSO). As for a longer timescale, Hu et al. (2012) suggested an interdecadal variation of the association of the QBO with Niño 3.4 SSTa. Yuan et al. (2014), analyzing radiosonde data of 10 near-equatorial stations, mostly from the 1950s, verified the effect of the ENSO that the QBO has a larger amplitude and a longer period during La Niña than during El Niño, with a less robust influence on the QBO amplitude than on the QBO period. Kawatani et al. (2019) reproduced realistic differences in the QBO between El Niño and La Niña by performing a 100-year simulation, respectively, of an atmospheric general circulation model under each SSTa condition. However, Dimdore-Miles et al. (2021), analyzing a 1000-year simulation of a coupled global climate model, showed that multi-decadal QBO amplitude variations are seemingly linked sporadically with Niño 3.4 SSTa.

In this paper, the presence of the decadal amplitude modulation of the QBO is provided as well as the decadal period modulation. The vertical and horizontal (latitudinal) structures are constructed through the composite analysis of the maximum and minimum phases in the decadal amplitude modulation. It is also shown that the decadal amplitude modulation of the QBO is positively correlated with the decadal components of Niño 3.4 SSTa and those of the Pacific Decadal Oscillation (PDO) as well. The rest of this paper is organized as follows. Section 2 describes the details of the radiosonde and reanalysis data, and the analysis methods. Section 3 gives the results, in which the aspects of the decadal components of the QBO are described in temporal and spatial cross sections. A discussion on the causes of the decadal modulations of the QBO is provided in Section 4, and the summary is presented in Section 5.

2. Data and methods

Updated equatorial FUB station data (Naujokat 1986) from 1953 to 2020 were used for the vertical range 70–10 hPa, wherein the following slight modification was made. Canton Island 10 hPa data, missing for the initial three years 1953–1955, were extrapolated upward/backward from the time series at 15 hPa assuming a vertical propagation rate of 2 km month⁻¹. These FUB data are referred to simply as Singapore data henceforth in this study because the data are comprised mostly of the Singapore data (1976–2020).

In addition, the merged reanalysis data of ERA-40 and ERA-Interim from 1958 to 2019 are used and referred to as ERArim, in which ERA-40 (1958–1988) and ERA-Interim (1989–2019) are continuously combined by adding the mean difference between them for 1988–1989 to ERA-40. The zonal-mean zonal wind of ERArim is utilized mostly as a latitudinally averaged form between 10°S and 10°N in this study, unless otherwise specified. Furthermore, Japanese 55-year Reanalysis (JRA-55) (Kobayashi et al. 2015) is used for a comparison of the low-frequency variations, such as the decadal variations in the QBO amplitude.

The datasets of Singapore, ERArim, and JRA-55 employed in this study span about 70 years from the 1950s to 2019 or 2020. However, the data after 2015 are not explicitly utilized for the evaluation of the QBO amplitude. In other words, the QBO amplitude is evaluated up to about 2015, and so is the QBO period. This is because of the suspension of the normal downward propagation of the easterly phase in 2015–2016. At that time, there was an anomalous upward displacement of the westerly phase from about 10 hPa to 15 hPa and, in addition, easterly winds develop at 40 hPa (Newman et al. 2016; Osprey et al. 2016). This disruption, referred to henceforth as the 2016 disruption, is an unprecedented phenomenon over the 70-year observation from 1953. Though seasonal forecasts did not predict this disruption, Watanabe et al. (2018) successfully reproduced this disruption in 40-day ensemble hindcasts with a global climate model, and demonstrated that a key to predict this disruption is simulating the slowly evolving mean winds in the winter subtropics. It should be noted that the effect of the 2016 disruption is inevitably, more or less, included in the QBO amplitude after about 2013 because the calculation of the QBO amplitude is made at the centers of the consecutive three cycles, as stated below.

Figure 1 displays the power spectrum of the zonal-mean zonal wind from 100 hPa to 1 hPa in the ERArim data from 1958 to 2019. Three dominant components appear, that is, a narrow spectrum of semiannual and annual oscillations, and a broad spectrum of the QBO. The QBO components are defined in this study as oscillations with periods from 20 months to 40 months, which cover the broad spectrum of the QBO but do not overlap other components, as shown in Fig.
1 and in other studies (Pascoe et al. 2005; Shibata and Lehmann 2020). A band-pass Lanczos filter (e.g., Duchon 1979) with cutoff periods at 20 and 40 months was applied to the monthly-mean time series of the zonal-mean zonal wind to derive the QBO components. As the QBO power maximizes in the vertical range at about 20 hPa (Fig. 1), the QBO characteristics were mainly investigated at 20 hPa in this study.

The QBO amplitude was calculated by two independent methods, that is, direct and wavelet methods, as in Shibata and Deushi (2012). The direct method assumes that the QBO amplitude is \( \sqrt{2\sigma} \), analogous to a monochromatic wave, where \( \sigma \) is the root mean square of the QBO time series over three cycles, even though the QBO time series is not a single sinusoidal wave (Pascoe et al. 2005; Baldwin and Gray 2005). One cycle is defined as a period from one zero point to the second consecutive zero point, that is, the next but one zero point, and the QBO amplitude is assigned to the center time of the three cycles. In this way, the QBO amplitudes are first calculated discretely in time, about a half cycle (~14 months) apart, and then, monthly amplitudes are obtained through a cubic interpolation with Lagrange polynomials. This procedure results in a QBO amplitude that is a low-pass filtered (>3 cycles ~7 years) data with a temporal resolution of about 14 months. Henceforth, this direct method is referred to as a sigma method.

The wavelet method provides a temporally local spectrum and was applied for the QBO analyses (Fadnavis and Beig 2008; Fischer and Tung 2008; Shibata and Deushi 2012; Sun et al. 2018). In this study, a Morlet mother wavelet (plane wave modified by a Gaussian envelope) with nondimensional frequency \( \omega_0 = 6 \) (e.g., Torrence and Compo 1998) was used, so that the result of the wavelet analysis incorporates average information within approximately three cycles centered at the time and frequency concerned. The QBO amplitude is evaluated as a square root of \( 2P_{QBO} \), where \( P_{QBO} \) is the sum of the wavelet power spectrum between 20 months and 40 months. A similar formula is used to calculate the wind amplitude at each discrete period.

Correlation coefficients between the decadal QBO and other physical quantities, such as F10.7 and SSTa, are calculated to investigate a possible causal relationship between them. A statistical test of correlation coefficients is evaluated by a Monte-Carlo simulation with phase randomization (e.g., Ebisuzaki 1997; Minobe and Nakanowatari 2002). In the simulation, a large number (10,000 in this study) of surrogate time series is generated by an inverse Fourier transform with the same power spectra as the original (QBO amplitude) time series but with random phases, and then, surrogate correlation coefficients with target signals, such as Niño 3.4 SSTa, are calculated. The relative position of the observed correlation coefficients in the sorted distribution of the surrogate correlation coefficients gives the level of confidence. Similarly, a lagged correlation of the decadal QBO between 20 hPa and other altitudes are also evaluated with the Monte-Carlo simulation.

3. Results

3.1. Decadal modulation

Figure 2 displays the QBO amplitude calculated by the wavelet from 70 hPa to 5 hPa, and the local wavelet power spectrum of the wind amplitude from 20 months to 40 months at 20 hPa for the ERArin zonal-mean zonal wind. The vertical range of larger
amplitudes is confined to approximately between 40 hPa and 7 hPa, wherein major power at 20 hPa resides in a period range from about 22 months to 36 months, similar to other altitudes (e.g., Pascoe et al. 2005). It is evident that there are decadal variations in both the QBO amplitude and period. In the Singapore data (Fig. 3), the QBO amplitude is larger than that latitudinally averaged between 10°S and 10°N, because the QBO amplitude of the zonal wind maximizes over the equator. The QBO period shows major peaks around 1965–1968, 1985–1990, 2001, and 2015, the range of which is from 28 months to 33 months. As stated above, the maximum peak (~33 months) around 2015 includes the effects of the 2016 disruption of the easterly phase, while there continues a prominent and gradual lengthening from about 2010. On the other hand, minimal periods ranging 24 months to 26 months occurred around 1960, 1972, 1997, and 2006. These decadal variations in the QBO period from 1965 to 2007 agree well with those analyzed by Fischer and Tung (2008), apart from the maximal period (28 months) around 2000 being shorter by 2 months in this analysis.

To demonstrate more clearly the decadal variations in the period and amplitude, time series of the QBO period (the average period of the three largest components in the local wavelet power) and those of the QBO amplitude at 20 hPa are drawn in Fig. 4 for the Singapore and ERAim data, respectively. The QBO period is almost the same if the period of the largest
component alone is used. The QBO period is nearly independent of heights (not shown) as in Fischer and Tung (2008), so that the period at 20 hPa can be used as a representative period of the QBO. The range of the period is from 24 months to 33 months, and that of the amplitude is from 17 m s\(^{-1}\) to 23 m s\(^{-1}\) for the ERArim data and from 19 m s\(^{-1}\) to 27 m s\(^{-1}\) for the Singapore data. It is difficult to estimate the phase relation between the period variations and the amplitude variations in Fig. 4. This is because the time series of the amplitude apparently include, to a certain degree, shorter (several years) period components, which hinder an evaluation of decadal components. The amplitude decadal variations can be evaluated more clearly by using the sigma method stated below.

Next, the decadal variations in the amplitude are treated in more detail. Figure 5 depicts the time series of the band-pass filtered zonal-mean zonal wind at 20 hPa, along with its QBO amplitude, calculated by the sigma method for the Singapore data from 1965 to 2020, and for the ERArim data from 1958 to 2019, respectively. The QBO amplitude for the JRA-55 data is also drawn in Fig. 5c. The low-frequency variations, including decadal variations in the ERArim and JRA-55 data, are similar over the entire period, with the difference being less than 0.5 m s\(^{-1}\) except for a QBO minimum around 1973 in the ERArim data. This relatively large difference around 1973 is in line with the fact that the correspondence between the two re-analyses and the radiosonde observations before 1978 are not comparable to those after 1979 (Harada et al. 2016).

Apparently, the QBO amplitude traces quite well the envelope of the band-pass filtered zonal-mean zonal wind for the Singapore and ERArim data. The sigma method results in nearly the same decadal variations and less short-period variations than the wavelet method, indicating that the sigma method works more effectively to filter out short-period components of less than a few years. The efficiency at reducing short-period components weakly depends on the number of QBO cycles, during which \(\sigma\) (root mean square) is evaluated. This is analogous to the characteristics of the moving average. Compared to the three-cycle evaluation, the one-cycle evaluation results in much larger decadal components with higher spurious short-period peaks, being similar to the QBO amplitude by the wavelet method (Fig. 4c). The two-cycle evaluation yields an intermediate time series of the QBO amplitude. Accordingly, the three-cycle evaluation is the best of the three in effectively diminishing short-period components, but yet retain-
ing decadal components.

A comparison of the decadal variations between the QBO period and amplitude (Figs. 4, 5) reveals that their phase relation was not consistent over the whole period, but inverted in the middle of the 1980s; that is, the two variations are approximately in-phase (correlated) before around 1985, and out of phase (anti-correlated) after that. The reason why the correlation reverses its sign from positive to negative around 1985 is currently unknown.

3.2. Structure of the decadal amplitude modulation

There are apparently four maximal amplitudes and three minimal amplitudes in the ERArim and Singapore data at 20 hPa (Fig. 5c) and their years are almost the same, although the ranges of the decadal variations are different in the two data. Henceforth, these maximal and minimal amplitudes of the QBO are referred to as QBO_{max} and QBO_{min}, respectively. The center years of QBO_{max} are around 1967, 1983, 1995, and 2005, while those of QBO_{min} are around 1973, 1988, and 2000. By compositing the QBOs in the ERArim data over relevant cycles for QBO_{max} and QBO_{min}, the vertical and horizontal structures of QBO_{max} and QBO_{min} were investigated, along with those of the climatological QBO. The reference phase for the composite is the QBO (band-pass filtered zonal wind) averaged between 5°S and 5°N at 20 hPa. One cycle, defined as a period from one interpolated zero (wind) to the second consecutive interpolated zero, is divided into equally spaced 28 intervals, that is, phases. In addition, the starting phase (phase-0) of the cycle is also defined as the interpolated transition time from easterly wind to westerly wind, as in Pawson et al. (1993). Hence, the second consecutive interpolated zero corresponds to phase-2π. The zonal wind in each phase is averaged over all the relevant cycles.

For the QBO_{max} composite, the four QBO_{max} values around 1967, 1983, 1995, and 2005 were used. Each QBO_{max} includes two consecutive cycles, the approximate periods of which are 1965/12–1970/12, 1979/11–1984/10, 1992/04–1996/11, and 2003/10–2008/01, respectively. On the other hand, the three QBO_{min} values around 1973, 1988, and 2000 were used for the composite QBO_{min}. Their approximate periods, comprised of two cycles, were 1970/11–1975/02, 1987/04–1992/05, and 1996/10–2001/07, respectively. Thus, the composite QBO_{max} and QBO_{min} are, in total, composed of eight and six cycles, respectively. Climatological QBOs are composited from 21 cycles from 1963/04 to 2012/10, which do not include the effect of the 2016 disruption of the QBO.
Figure 6 exhibits the composite vertical structure (phase–height cross section) of the climatological QBO, QBO_{clim}, over one cycle and that of the difference between QBO_{max} and QBO_{min}, that is, QBO_{max} − QBO_{min}, for the ERArim data averaged between 10°S and 10°N. The climatological QBO is symmetric with respect to duration and strength between westerly and easterly phases because of the use of the band-pass filtered wind, in contrast to the asymmetric structure composited from raw wind (Pawson et al. 1993; Huang et al. 2012). The downward steady propagation of each phase forms a plateau of larger amplitude (> 16 m s\(^{-1}\)) from 10 hPa to 30 hPa, with a maximum of about 19 m s\(^{-1}\) at 20 hPa in the climatological QBO. The difference QBO_{max} − QBO_{min} has a maximum amplitude of about 3 m s\(^{-1}\) at 20 hPa and shows nearly the same downward propagation speed as the climatological QBO below 20 hPa, above which there is no downward propagation, that is, in-phase oscillation. The difference QBO_{max} − QBO_{min} lags behind QBO_{clim} by about 3 months in the westerly phase, while it is nearly in-phase with QBO_{clim} in the easterly phase below 20 hPa. On the other hand, the difference between QBO_{clim} and QBO_{min} is a qualitatively similar vertical structure to QBO_{max} − QBO_{min}, while QBO_{clim} − QBO_{min} is quantitatively less than half as large as QBO_{max} − QBO_{min}.

Figure 7 displays the composite horizontal structure (phase–latitude cross section) of the climatological QBO over one cycle, and that of the difference QBO_{max} − QBO_{min} for the ERArim data at 20 hPa. The climatological QBO has a maximum amplitude of about 24 m s\(^{-1}\) over the equator, and the patterns of both phases are similarly rounded, being almost symmetric with respect to the equator. The phase change initiates in the northern vicinity of the equator for both phases, which lacks observed asymmetric features that easterly accelerations begin at the equator and westerly accelerations start simultaneously across the equator (Dunkerton and Delisi 1985; Huesmann and Hitchman 2001). This also stems from the use of the band-pass filtered wind, as stated above. The difference QBO_{max} − QBO_{min} at 20 hPa has off-equator extrema of about 3.5 m s\(^{-1}\) around 5°N and 3°N, respectively, for the westerly and easterly phases, while the phase change in QBO_{max} − QBO_{min} first starts in the southern vicinity of the equator, and the resultant phase propagates equatorward and then outward. These features are qualitatively similar at 30 hPa, except for the value of the extrema (not shown).

At 10 hPa, the difference QBO_{max} − QBO_{min} straddles the equator, so that two extrema appear in both the westerly and easterly phases (Fig. 8). The extrema in the westerly are situated around 13°N and 7°S, while those in the easterly are around 9°N and 4°S. On the other hand, in the lower stratosphere below 50 hPa,
the extrema occur in the Southern Hemisphere, around 5°S at 50 hPa (Fig. 9), and around 2°S and 5°S for the negative and positive extrema, respectively, at 70 hPa (not shown). The difference $QBO_{\text{clim}} - QBO_{\text{min}}$ is a qualitatively similar structure to $QBO_{\text{max}} - QBO_{\text{min}}$, while $QBO_{\text{clim}} - QBO_{\text{min}}$ is quantitatively about half as large as $QBO_{\text{max}} - QBO_{\text{min}}$.

Figures 7–9 indicate that $QBO_{\text{max}} - QBO_{\text{min}}$ is not symmetric with respect to the equator, with different off-equatorial components at different altitudes, in distinct contrast to the symmetric structure over the whole depth of the climatological QBO. This suggests...
that synoptic-scale waves (e.g., Plumb 2002) propagating from the sub- and extratropics may play a role in producing the asymmetric components in the lower stratosphere. On the other hand, planetary waves (e.g., Lu et al. 2014) propagating from the extratropics may also be involved because at higher altitudes (e.g., at 10 hPa), the asymmetric components extend beyond the subtropics to the mid-latitudes in the Northern Hemisphere. However, to explore this topic is beyond the scope of this paper.

4. Discussion

The cause of the decadal modulation in the QBO is still unresolved. Generally, there are two candidates for the cause of the QBO modulation, “top-down” and “bottom-up” mechanisms, that is, the solar activity (e.g., Salby and Callaghan 2000) and SSTa in the tropics (e.g., Taguchi 2010), respectively. The solar maximum associated with the 11-year solar cycle induces anomalous radiative heating and ozone increase in the tropical upper stratosphere and above through the intensified irradiance at shorter wavelengths in the ultraviolet radiation (e.g., Gray et al. 2010). This influence is supposed to propagate downward through changes in the thermal structure and in the mean meridional circulation, which results in the modulation of the QBO (e.g., McCormack 2003; Pascoe et al. 2005). On the other hand, SSTa in the tropics induces substantial changes in the convective activity, which modify the generation of the waves propagating to the stratosphere (e.g., Kawatani et al. 2019) as well as the tropospheric circulation (e.g., Hu et al. 2012).

Before the calculation of correlation coefficients between the QBO amplitude and the candidates, the direct and linear components are subtracted from the QBO amplitude, that is, the deviation from a linear fit is treated for the QBO amplitude. This is because the main concern is the decadal components and there are apparent linear trends in the QBO amplitude in the ERArim and Singapore data (Figs. 4c, 5c). The magnitude of the trend up to 2012 at 20 hPa is about 0.6 m s$^{-1}$ decade$^{-1}$ and 0.9 m s$^{-1}$ decade$^{-1}$, respectively, for the ERArim and Singapore data, the latter of which is nearly the same as Kawatani and Hamilton (2013).

Figure 10 depicts the time series of the QBO amplitude deviation (m s$^{-1}$) from a linear fit at 20 hPa for the ERArim data, along with the time series of decadal components of Niño 3.4 SSTa (°C) (1981–2010 base period, Huang et al. 2017) and F10.7 (10$^{-22}$ W m$^{-2}$ Hz$^{-1}$), both of which are low-pass filtered to periods longer than 96 months (8 years). The low-pass filtering led to a substantial reduction in the decadal amplitude of Niño 3.4 SSTa (~ 0.5°C) from the monthly amplitude (2–2.5°C), while there is scarcely any reduction for F10.7. The QBO amplitude is evidently in-phase with the decadal Niño 3.4 SSTa over the whole period except after ~ 2013, during which the effect of the 2016 disruption is inevitably included.
in the QBO amplitude evaluation by the sigma method (Fig. 5). The correlation coefficient of the QBO amplitude with the decadal Niño 3.4 SSTa is 0.72, wherein the interpolated monthly variables are used during the period of the QBO amplitude assignment from 1962 to 2012, excluding the effect of the 2016 disruption. The correlation coefficient is nearly the same even when the intrinsic interval (~ 14 months) of the QBO amplitude assignment is employed. The correlation coefficient of 0.72 is statistically significant at the 5 % level.

The QBO amplitude is also closely correlated with the decadal equatorial southern oscillation index (SOI) (not shown) because the SOI represents one aspect of the responses of the tropical atmosphere to SSTa in the tropical Pacific (e.g., Philander 1989). The correlation coefficient with the decadal equatorial SOI is −0.74, which is also significant at the 5 % level. This indicates that the “bottom-up” mechanism due to SSTa is certainly responsible for the decadal amplitude modulation of the QBO.

On the other hand, the decadal F10.7 is correlated neither with the amplitude modulation (Fig. 10) nor with the period modulation (Fig. 4) of the QBO, as pointed out by other studies (e.g., Hamilton 2002; Fischer and Tung 2008). The correlation coefficient with the decadal F10.7 is an insignificant value of 0.13, which situates about 30 % in the sorted distribution of the surrogate correlation coefficients. This holds true even when the monthly F10.7 is used (not shown), because its dominant power spectrum is concentrated around 11 years. Indeed, the solar cycle does induce decadal variations in the thermal structure and ozone field through the solar irradiance variations, particularly at the shorter ultraviolet wavelengths, in the tropical stratosphere and above (Gray et al. 2010 and references therein). However, the insignificant correlation between F10.7 and the QBO amplitude indicates that the “top-down” mechanism does not explain the decadal modulation of the QBO over the whole period from the 1950s to the 2010s.

Figure 11 depicts the evolution of the QBO amplitude at each altitude (pressure) from 70 hPa to 10 hPa for the ERAir and Singapore data. The downward propagation of the QBO amplitude can be apparently seen in the Singapore data, while the ERAir data scarcely show such a feature, except for 70 hPa. Quantitatively, a lagged correlation analysis of the detrended QBO amplitude between 20 hPa and other altitudes in the Singapore data indicates that the maximum correlation (0.72 significant at the 1 % level) occurs at about 1 year at 50 hPa, with the maximum (0.63 significant at the 5 % level) at zero lag at 10 hPa, meaning that the QBO amplitude at 50 hPa is retarded about 1 year from that at 20 hPa and that there is no time lag between 20 hPa and 10 hPa. Although the lag and maximum correlation coefficient differ depending on altitudes and periods, the statistical significance is
high throughout the period. On the other hand, in the ERArim data, the time lag is almost zero from 50 hPa to 10 hPa, with a slight lag of about a half year at 70 hPa. In addition, the maximum correlation coefficient and the statistical significance are lower before 1980. For example, the maximum correlation coefficient at 50 hPa is 0.83 (significant at the 1% level) for 1980–2012, while it is 0.38 (significant at the 10% level) for 1958–2012.

It should be noted that the QBO amplitude at 10 hPa is advanced slightly by 3–7 months for 1980–2012 in both the data, in spite of zero lag for the whole period. The downward propagation or zero lag of the QBO amplitude indicates that the decadal modulation of the QBO due to the decadal SSTa in the tropical Pacific also initiates in the upper stratosphere as the intrinsic phase evolution within each cycle of about a 28-month period. Hence, the phase relation between the QBO amplitude and the decadal SSTa has, more or less, a time lag at a pressure different from that at 20 hPa (Fig. 11). The downward propagation or zero lag of the QBO amplitude also indicates the correlation between the QBO amplitude and F10.7 to be insignificant not only at 20 hPa but also at other altitudes.

A close comparison of the QBO amplitude evolution between the ERArim and Singapore data reveals that the synchronization of the decadal modulation between the two data are evidently seen at each pressure except for that at 10 hPa before about 1980, during which the QBO amplitude is steadily decreasing in the ERArim data, while it remains nearly constant in the Singapore data. This discrepancy at 10 hPa between the two data before about 1980 seems to be larger than the longitudinal variations of the QBO amplitude, which exceed 10% at that altitude (Hamilton et al. 2004).

Another candidate causing the decadal amplitude modulation of the QBO is the PDO, defined as the leading empirical orthogonal function (EOF) of monthly SSTa poleward of 20°N in the Pacific basin (Mantua et al. 1997). Wang et al. (2016) presented, using a reanalysis for 1979–2014, and climate model simulations for 145 years, evidence of a link between decadal variability in tropical tropopause temperature and the PDO. In the negative phase of the PDO, there occurs a warmer tropopause over the central equatorial Pacific through a weaker Hadley Circulation. In addition, the weakened Brewer–Dobson circulation resulting from less wave propagation into the stratosphere contributes to the warmer tropical tropopause. The resultant decadal variations in the thermal structure near the tropical tropopause can modify the generation and filtering of the waves propagating upward, leading to modulation in the momentum deposition due to the waves. As a result, the decadal amplitude modulation of the QBO is initiated in the upper stratosphere.

Figure 12 displays the time series of the decadal component of the PDO index together with that of the North Pacific gyre oscillation (NPGO) index (Di Lorenzo et al. 2008), wherein monthly values of both indices were taken from the Japan Meteorological Agency (JMA) and a Lanczos low-pass filter with a
cutoff period at 96 months was applied to derive the decadal components. The NPGO index is calculated as the second EOF of SSTa poleward of 20°N in the Pacific basin (JMA, https://www.data.jma.go.jp/gmd/kaiyou/data/shindan/b_1/pdo/pdo.html). Although the monthly data of the two indices are independent (orthogonal) of each other, their decadal components behave nearly in parallel. Similar parallel behavior can also be seen when cutoff periods of 60 months and 132 months are applied. Figure 12 indicates that the PDO and NPGO indices are positively correlated with the amplitude of the QBO (Fig. 10a), similar to the decadal Niño 3.4 SSTa. The correlation coefficients of the decadal QBO with the decadal PDO and NPGO indices are 0.82 and 0.64, respectively, and the two coefficients are statistically significant at the 0.1 % and about the 1 % levels, respectively.

These positive correlations suggest that the major cause of the impact of the PDO and NPGO on the QBO amplitude is associated with the Central Pacific warming (CPW) El Niño pattern (Di Lorenzo et al. 2010). This is because the SSTa regressed on the NPGO index resembles the CPW or equivalently El Niño Modoki (Ashok et al. 2007), and the SSTa regressed on the PDO index shows a similar CPW (Mantua et al. 1997). This is in line with the high positive correlation of the decadal Niño 3.4 SSTa with the QBO amplitude (Fig. 10), stemming from the fact that the CPW El Niño pattern overlaps with the Niño 3.4 region to a large extent.

However, the phase relation between the QBO amplitude and the decadal Niño 3.4 SSTa is opposite to that between the QBO amplitude and Niño 3.4 SSTa in the intrinsic ENSO timescale, that is, the former correlation is positive, while the latter correlation is negative. In other words, positive decadal Niño 3.4 SSTa is related to a larger QBO amplitude (Fig. 10), whereas intrinsic positive Niño 3.4 SSTa is linked to a smaller QBO amplitude (Taguchi 2010; Yuan et al. 2014). Also, as for the QBO period, the impact of Niño 3.4 SSTa is different depending on the timescale. In the intrinsic ENSO timescale, the QBO period is shorter during El Niño through faster phase propagation than during La Niña (Taguchi 2010; Yuan et al. 2014). In contrast, the correlation between the QBO amplitude and period in the decadal timescale did not remain consistent, but reversed the sign from positive to negative around 1985, as stated before. Nevertheless, it is certain that variations in the convective activity in the tropical Central Pacific modulates the generation of the waves propagating to the stratosphere, resulting in the modulation in the QBO amplitude in the decadal timescale as well as in the ENSO timescale. To explore the positive correlation between the QBO amplitude and the decadal Niño 3.4 SSTa in more detail is a future work.

5. Summary

Decadal modulations of the QBO in the equatorial stratosphere were investigated for an altitude range from 70 hPa to 10 hPa, using the Singapore data from 1953 to 2020 compiled by the FUB and the merged data of ERA-40 and ERA-Interim from 1958 to 2019. The QBO amplitude was calculated by two independent methods: the sigma method and the wavelet method. The sigma method evaluates the QBO amplitude through an approximation that the QBO is close enough to a monochromatic wave over three cycles, resulting in the low-pass filtered QBO amplitude, the period of which is longer than three cycles ~ 7 years. The wavelet method is also used to evaluate the decadal modulation of the QBO period, which is defined as the average period of the three largest local wavelet power components.

It is found that the QBO is decadally modulated in the amplitude as well as in the period. The phase rela-
tion between the decadal variations in the amplitude and the period is found to reverse its polarity around 1980, that is, the two variations are negatively correlated with each other after the 1980s, while they are approximately positively correlated before the 1980s. This suggests that the cause of the amplitude modulation is different from that of the period modulation.

In the time series of the QBO amplitude from the 1950s to 2014, there are four maxima, $QBO_{\text{max}}$, around 1967, 1983, 1995, and 2005, and three minima, $QBO_{\text{min}}$, around 1973, 1988, and 2000. Composite analyses of $5^\circ\text{N}$ at 20 hPa revealed that the decadal amplitude variations had a maximum amplitude of about 3 m s$^{-1}$ at 20 hPa in the vertical. In the horizontal structure, off-equator extrema of about 1.8 m s$^{-1}$ appeared around $5^\circ\text{N}$ at 20 hPa, while extrema of about 1.8 m s$^{-1}$ were situated around $5^\circ\text{S}$ at 50 hPa. The decadal amplitude variations of the QBO were highly correlated with the decadal components of Niño 3.4 SSTa and PDO, suggesting that the tropical SSTa in the Central Pacific substantially influences the QBO amplitude in the decadal timescales.

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