

Non-stationary Synchronization of Equatorial QBO with SAO in Observation and in Model

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Abstract

It has often been suggested that the period of the Quasi-Biennial Oscillation (QBO) has a tendency to synchronize with the Semi-Annual Oscillation (SAO). Using 45 years of ERA-40 data of the equatorial stratosphere up to the stratopause, we demonstrate that this synchronization is not just a tendency but indeed holds quite well in the upper stratosphere. A QBO period starts when a SAO westerly descends from the stratopause to 7 hPa and initiates the westerly phase of the QBO below, and it ends when another SAO westerly, a few SAO periods later, descends again to 7 hPa to initiate the next westerly QBO. That it is the westerly and not the easterly SAO that initiates the QBO is also explained by the general easterly bias of the angular momentum in the equatorial stratosphere so that the easterly SAO does not create a zero-wind line, unlike the westerly SAO. The currently observed average QBO period of 28 months, which is not an integer multiple of SAO periods, is a result of intermittent jumps of the QBO period from 4-SAO periods to 5-SAO periods. The same behavior is also found in a model, the two-and-a-half dimensional THINAIR model. We find that the non-stationary behavior in both observation and model is not caused by the variable solar-cycle forcing, but is instead caused by the incompatibility of the QBO's natural period determined by its wave forcing, and the quantized period determined by the SAO. The wave forcing parameter for the QBO period in our current climate probably lies between 4-SAO and 5-SAO periods. If the wave forcing for the QBO is tuned in a parametric study so that its natural period is compatible with the SAO period above, e.g. at 24 months, 30 months or 36 months, non-stationary behavior disappears.

1. Introduction

The Quasi-Biennial Oscillation (QBO) is an internal oscillation of the equatorial zonal wind in the stratosphere involving wave-mean flow interactions (Holton and Lindzen, 1972; Lindzen and Holton, 1968; Dunkerton, 1997; Baldwin *et al.*, 2001). There have been numerous observational studies of the QBO in the zonal wind, temperature, and ozone (e.g., Angell and Korshover, 1970; Oltmans and London, 1982; Hasebe, 1983; Zawodny and McCormick, 1991; Randel *et al.*, 1996; Pawson and Fiorino, 1998). The equatorial QBO affects the polar stratosphere during winter, with the easterly phase of the QBO (e-QBO) creating the condition for a more perturbed and warmer polar vortex (Holton and Tan, 1980, 1982; Baldwin and Dunkerton, 1999, Ruzmaikin *et al.*, 2005). Therefore, the variation of the QBO period has additional significance, especially with respect to the timing of its phase relative to the Northern winter in what is called seasonal synchronization (Baldwin *et al.*, 2001).

The period of the QBO currently averages to about 28 months but is known to have inter-annual variations of several months about the average. When the QBO was first discovered (Reed *et al.*, 1961; Ebdon and Veryard, 1961), it was found to have a period of 26 months, 13 months each of easterly and westerly phases at 50 hPa. Later it was reported (Tung and Yang, 1994) to have a period of 30 months (for satellite record of 1979-1992). For the period 1958-2002 spanned by the ERA-40 data (Uppala *et al.*, 2005), the mean QBO period is slightly less than 28 months (see below). It becomes a little longer than 28 months using the longest data (rocketsonde and

rawinsonde) (1953-2007) available from Free University of Berlin (FUB) (Baldwin *et al.*, 2001; Fischer and Tung, 2008). It is interesting to point out that the length of QBO periods is not constant but is quite variable. The mean period of 28 months does not apply to individual QBO episodes; the latter tend to be a multiple of the period of Semi-Annual Oscillations (SAO). For example, the current estimate of 28 months as the mean QBO period is composed of a collection of individual periods of approximately 24 months and 30 months (and an occasional 36 months in the longest records). Since the SAO is seasonally synchronized, with respect to Northern and Southern winters, the tendency of the QBO to synchronize with the SAO may be an important cause of seasonal synchronization.

As pointed out by previous authors (Lindzen and Holton, 1968; Gray and Pyle, 1989; [Le:pls add reference] Dunkerton and Delisi, 1997), the SAO's alternating easterly and westerly shear zones near the stratopause level serve to "seed" the QBO below. In particular, the onset of the westerly QBO is tied to the downward propagation of the westerly phase of the SAO. A QBO period starts with the zero-wind line associated with the westerly shear zone of the SAO descending into the QBO region below, and ends when the next such westerly descent occurs, at a multiple of SAO periods later, to replace the easterly QBO below. In this way the QBO period is quantized in units of the SAO period. Lindzen and Holton (1968) found that "the appearance of successive westerly regimes at 30 km tends to be a multiple of 6 months". Since it is thought that there may be other factors that can affect the descent rate of the QBO from the upper to the lower stratosphere, in the lower stratosphere this property has been regarded more as a "tendency" than a strict synchronization in reality (Dunkerton and Delisi, 1997). The recent result of Fischer and Tung (2008) that the individual period of the QBO is almost constant with height from the lower

stratosphere to the upper stratosphere, where there is strong synchronization with the SAO, implies that even in the lower stratosphere there should be a near synchronization, within an accuracy of 1-2 months.

This paper is divided into 5 sections. In section 2, we will show using the ERA-40 reanalysis data (Uppala *et al.*, 2005), which extends to the stratopause, that in fact the QBO period is better synchronized with the SAO than previously thought. We will also show that the decadal variation in the QBO period previously reported often takes the form of a quantum jump in integer multiples of SAO period. In section 3, we will explain using a model why the QBO period variation is non-stationary in our current climate. A possible mechanism for QBO-SAO synchronization will be discussed in section 4 and it will be followed by conclusions in section 5.

2. QBO-SAO Synchronization: Data Analysis

Figure 1 shows the height-time cross-section of the equatorial zonal wind in the ERA-40 dataset up to 1 hPa. Baldwin and Gray (2005) compared the ERA-40 reanalysis zonal winds with the tropical rocketsonde and rawinsonde observations, and concluded that the reanalysis provides “a good representation of tropical winds up to 2-3 hPa. The amplitudes of the quasi-biennial oscillation (QBO) and the semi-annual oscillation (SAO) derived from ERA-40 data match the rawinsonde and rocketsonde observations up to 2-3 hPa.” They further suggested that “zonal-mean ERA-40 winds could be used, for most purposes, in place of rawinsonde station observations.”

The 2-7 hPa region is where the SAO, which is prominent in the stratopause level above, transitions to the QBO below. The presence of the QBO makes parts of the SAO difficult to see in the raw data shown in the first two panels of Figure 1: During a QBO easterly phase, the westerly and easterly

phases of the SAO is imbedded in an easterly background and show up only as relative easterly maxima and minima. The alternating easterly and westerly phases of the SAO are seen when we remove the QBO by averaging over all Januaries, Februaries etc in the entire ERA-40 record. This is done in the last two panels in Figure 1 for 1-3 hPa. It is also seen in Figure 1 that the westerly QBO always starts with a westerly SAO above, and one period of the QBO terminates when the westerly phase of the following QBO starts similarly with the descent of another westerly SAO. The reason that it is the westerly phase of the SAO, and not its easterly phase, that initiates a QBO below is explained below: Since the equatorial upper stratosphere is easterly without the SAO, the easterly SAO does not introduce a zero-wind line, but the westerly SAO does. A zero-wind line is where enhanced wave-mean flow interaction occurs. Therefore, at and immediately below the zero-wind line introduced by the westerly SAO, westerly wave momentum is deposited, causing the descent of the westerly shear zone, *provided that* the westerly waves are allowed to propagate up from the lower to the upper stratosphere. This happens when the westerly shear zone at the 50-70 hPa region, which shields waves of westerly phase speeds from propagating upward, breaks down at the appropriate time in the QBO's life cycle (see later). Therefore not all westerly SAOs initiate a QBO. Since a QBO period always starts and terminates with a westerly SAO, the period of the QBO should be an integer multiple of the SAO period.

Figure 2a shows that in fact this is the case, when the QBO period is measured in units of the SAO period, as described in the following. A QBO period is measured by the time interval between the two zero crossings when the wind shifts from easterly to westerly. Instead of measuring it in months, we measure the QBO period at 5 hPa by counting the number of SAO periods above that level shown in Figure 1. There are a few instances when a SAO westerly descends to the QBO altitude at

5 hPa but for some reason stalls there and fails to initiate a QBO below that level. One such example is just before 1963. The QBO period starts instead with the next SAO. Another such case occurs during the QBO of 1987-89. In this case it is clear, by looking at the QBO below 10 hPa, that the failed initiation of the QBO in mid 1986 should not be regarded as the starting point of the QBO, which actually started in 1987, one SAO period later.

Figure 2b is the histogram of the number of occurrences when the QBO period is 4- or 5-SAO in the 45-year ERA-40 data. It is seen that the reported mean period of 28 months (the exact value is 27.7 months) for the QBO during this period of record is an average of seven QBO periods each lasting 4-SAO periods (on average 24 months), and eleven QBO periods when it is 5-SAO periods (on average 30 months). In Figure 2c, we show the vertical profiles of two individual QBO periods (one starting in 1962 (4-SAO) and the other in 1997 (5-SAO), along with the mean period of all the QBOs in the ERA-40 record. We see that, not surprisingly, the mean QBO period is constant with height (as also shown in Figure 2c of Gabis and Troshichev (2006)). Individual QBO periods are slightly more variable, but can be regarded as almost constant, within ± 1 month between 1-40 hPa, consistent with Fischer and Tung (2008).

Figure 2a shows that there are interesting decadal variations in the QBO period, and that such variation takes the form of quantum jumps in integral multiples of SAO periods. What causes the decadal variation of the QBO period in the lower stratosphere is a topic of current debate (Salby and Callaghan, 2000; Soukharev and Hood, 2001; Pascoe et al, 2005; Hamilton, 2002; Fischer and Tung, 2008). It is however apparent from this figure that such changes in QBO period in the upper stratosphere are not correlated (or anti-correlated) with the 11-year solar cycle (SC); the total solar

irradiance (Lean, 2004) is indicated by the solid curve at the bottom of Figure 2a. Note, however, that this result concerns the whole period of the QBO and does not necessarily apply to the question of whether the westerly portion of the QBO is correlated with the solar cycle.

An additional interesting result is that the jumps in the QBO period that we see in the ERA-40 data (in Figure 1 or 2) above is not only seen in our model result (to be presented later) with a periodic solar cycle forcing, but is also present in model runs with perpetual solar maxima (SC-max) or solar minima (SC-min) or solar mean (SC-mean) forcing. This suggests that the non-stationary jumps in QBO period is probably not a result of the variable solar-cycle forcing, but is a property intrinsic to the QBO phenomenon itself.

3. QBO from THINAIR Model

The Model

The THINAIR (Two and a Half dimensional INterActive Isentropic Research) is an isentropic coordinate chemical-radiative-dynamical model (Kinnnersley and Harwood, 1993). The model has zonally averaged dynamics and includes the three longest planetary waves, which are prescribed by observations at the tropopause level. For this study, the planetary wave forcing at the tropopause is fixed at the 1979 year level derived from NCEP reanalysis data (Kalnay, *et al.*, 1996; Kistler, *et al.*, 2001), annually periodic and repeated for all years. This choice reduces inter-annual variability of the planetary wave forcing, so that this variability in forcing is eliminated as a cause of the observed non-stationary behavior of the QBO period. It removes tropospheric variability of planetary waves, but retains stratospheric variability of the planetary waves that is internally generated through wave propagation in a changing mean flow and wave-mean flow interaction. The model uses an

isentropic vertical coordinate above 350 K. Below 350 K a hybrid coordinate is used to avoid intersection of the coordinate layers with the ground. The version used in this study has 29 layers from the ground to ~100 km for dynamics and 17 layers from ground to ~60 km for chemistry. The model has 19 meridional grid points evenly distributed from pole to pole. The QBO-source term in the momentum equation uses parameterization of wave momentum fluxes from Kelvin, Rossby-gravity and gravity waves (Kinnersley and Pawson, 1996). These momentum sources also force the SAO above the QBO.

UARS/SUSIM spectral irradiance observation is used for the 11-year SC. UARS/SUSIM data consists of the solar spectrum in 119-400 nm during 1991-2002, with 1-nm resolution. The monthly data are extended to 1947-2005 using F10.7-cm as a proxy (Jackman, *et al.* 1996). The yearly averaged data are integrated to give photon fluxes in wavelength intervals appropriate for the THINAIR model. The performance of the model has been reported in the literature (Kinnersley and Pawson, 1996). To avoid redoing the climatology with the new solar forcing, the UARS/SUSIM SC-mean is scaled to the SC-mean of the THINAIR model, which was based on Lean (2004).

Time-varying solar cycle run

Two-hundred year runs are made using the realistic, time varying solar cycle forcing for 1964-1995 from UARS/SUSIM (extended as described above) and repeated thereafter. Even in this long run, the period of the QBO does not settle down to a fixed number, but still executes apparently irregular jumps in period. Another 400-year run is carried out to show that the statistical properties in the 200-year run has settled down (in particular the histograms of the distributions for the 200-year run and the 400-year run are the same). The behavior of the QBO period in the model is quite similar to

the observed discussed above. In particular, the QBO period jumps from 4-SAO periods to 5-SAO periods and back, in a non-stationary manner. Figure 3 shows a height-time cross section of the zonal mean zonal wind at the equator from the model. Figure 4 can be used to compare the period of model QBO with that from ERA-40 shown in Figure 2. The number of 5-SAO periods is about equal to the number of 4-SAO periods in both the 200- and 400-year runs and so the frequency of the 5-SAO periods relative to the 4-SAO periods is less than in the 45 years of the ERA-40 data. However, in different smaller time segments of about 45 years corresponding to the period of ERA-40 data, the distribution can shift. In the segment shown, which is from year 126 to year 172 in the 400-year model run, there are more 5-SAO periods than 4-SAO periods, as in the ERA-40 data.

Perpetual solar forcing runs

Additionally, we perform constant solar-cycle forcing experiments in our model to answer the question of whether the non-stationary nature of the QBO period is caused by the fact that the solar-cycle forcing is time-varying. (It should be pointed out that we still have the seasonal cycle in perpetual solar runs.) Figure 5 is similar to Figure 3 except for perpetual SC-mean forcing, in the 400-year runs. There are no qualitative differences between the perpetual solar forcing run and the variable solar-cycle forcing run. In particular, the QBO period still jumps irregularly from 4-SAO periods to 5-SAO periods and back. We therefore conclude that the non-stationary nature of the QBO period is not caused by the fact that the solar-cycle forcing is time-varying on decadal time scale.

4. A Possible Mechanism for QBO-SAO Synchronization

In the original theory of the QBO by Lindzen and Holton (1968) the presence of the mesospheric SAO above the QBO is needed to restore the flow to a direction that is opposite to the zonal flow at

the lower stratosphere. Later publications, however, have tended to deemphasize the essential role of the SAO in seeding the QBO, following the conclusion of Holton and Lindzen (1972) that “The mesospheric semiannual oscillation, while important, is no longer absolutely essential to the overall theory” (Holton was reportedly uneasy with this statement; see Lindzen (1987)). Plumb (1977) also argued that the SAO is unnecessary for the QBO. Neither model, however, incorporated the easterly bias of the equatorial zonal flow on a rotating planet: without the SAO the equatorial upper stratosphere near the stratopause is generally easterly, making it difficult for initiating a westerly QBO. Note that the assumed form of mean zonal flow is westerly in the upper stratosphere in the original model of Lindzen and Holton (1968), and there is a SAO in the numerical model of Holton and Lindzen (1972) that provided the westerly flow in the upper levels. While it is not “absolutely essential” to have the SAO since a highly nonlinear wave breaking event can initiate a westerly descent by itself, without the SAO the initiation of the westerly descent probably would have occurred higher up, in the mesosphere.

As the westerly QBO descends into the lower stratosphere with denser and denser air, it stalls usually at the 70 hPa level. Upward propagating waves with phase speeds in the same direction as the lower stratospheric zonal flow, westerly in this phase of the QBO, meet their critical level in the lower stratosphere (where the phase speed equals the mean wind speed) and are absorbed near or below this level. They are thus prevented from propagating further upward. Waves of opposite (easterly) phase speeds can however freely propagate up. These (easterly) waves encounter an easterly zonal flow, deposit their easterly momentum and subsequently bring the easterly jet to lower and lower altitudes, replacing the westerly flow below it. In the simple models mentioned above, the westerly jet near 70 hPa becomes thinner and thinner in the process, and eventually

breaks due to flow instability. This then allows the propagation of westerly waves into the upper stratosphere. Since the equatorial upper stratosphere and mesosphere are generally easterly without the SAO, these westerly waves do not meet their critical level and the descent of the westerly zonal flow cannot be initiated (in the quasi-linear model of Lindzen and Holton (1968)) in the absence of the SAO. Therefore the SAO plays an important role in initiating the alternating easterly and westerly descents of the zonal wind in a QBO. It follows then that the period of the QBO, at least in the upper stratosphere, should be synchronized with the SAO. In particular, the westerly phase of the QBO should be synchronized with the westerly phase of the SAO, as it is observed to do in the ERA-40 data presented in section 2. The initiation of the easterly phase of the QBO does not need the SAO.

The above discussion explains that, given there is a SAO at the stratopause, the initiation of the westerly phase of the QBO should be synchronized with the westerly phase of the SAO. It then follows that the QBO period in the upper stratosphere should be an integer multiple of the SAO period. The remaining question is, why does the QBO period jump from one SAO multiple to another SAO multiple? One suggestion could have been that it is the variable solar-cycle forcing that alters the QBO period, but this effect is found to be negligible in our model. There is no correlation or anti-correlation of the QBO period with the solar cycle in either the observation or in the model. (We are not addressing here the issue of whether the westerly duration of the QBO is anti-correlated with the solar cycle, as reviewed by Fischer and Tung (2008); the modeling work is left to a separate paper.) Furthermore, we find that the non-stationary jumps still occur even when there is no solar-cycle variability. An explanation of this non-stationary behavior appears to be the following: the intrinsic period of the QBO is determined by the internal dynamics of the wave-

mean flow system. Plumb (1977) gave a simple formula for the simplified cases: the period T is proportional to the cube of the phase speed c of the forcing wave and inversely proportional to the magnitude of the wave forcing F . This intrinsic period, however, may not be compatible with the period determined by the SAO. For the case where the intrinsic QBO period lies between 4-SAO and 5-SAO periods, a predicted transition from easterly to westerly QBO would have to occur in a SAO easterly flow, which is difficult. Instead the transition would be delayed or advanced to the nearest westerly SAO phase. Non-stationary jumps are needed so that the long term averaged period is close to the intrinsic period. Compatibility with the QBO's period is necessary, and explains why not all westerly SAOs initiate a QBO. As discussed previously, the initiation of the westerly phase of the QBO by an westerly SAO has to wait until in the life cycle of the QBO in the lower stratosphere when westerly equatorial waves are not blocked from propagating upward.

If the intrinsic period of the QBO is already an integer multiple of the SAO period, the QBO period would be phase-locked with that SAO multiple and the nonstationary jumps would disappear, if this explanation is correct.

Parametric study

We can test this hypothesis in our model in a parametric study by changing the QBO wave forcing F . The westerly forcing by a Kelvin wave is parameterized as in Gray and Pyle (1989), while the easterly forcing in this model by Rossby-Gravity wave differs from the Kelvin wave only in its opposite zonal phase speed (Kinnersley and Pawson, 1996). The expression for the wave-induced zonal force per unit mass is defined as following by (Gray and Pyle, 1989):

$$F(z) = \exp\left(\frac{z-z_0}{H}\right) \sum_{i=1}^2 A_i R(z, c_i) \exp(-P_i(z)) \quad (1)$$

where

$$R(z, c_i) = \frac{\alpha(z)N}{k_i(\bar{u} - c_i)^2} \quad (2)$$

$$P_i(z) = \int_{z_0}^z R(z) dz \quad (3)$$

Here $i=1$ is for the Kelvin wave and $i=2$ is for the Rossby-Gravity wave. $c_1 (>0)$ is the phase speed (m s^{-1}) for Kelvin wave while $c_2 (<0)$ is the Rossby-Gravity wave phase speed. A_i is the amplitude of vertical momentum flux at z_0 in unit ($\text{m}^2 \text{s}^{-1}$). For the baseline case in Figure 6b, $A_1=2.7 \times 10^{-3} \text{ m}^2 \text{s}^{-1}$ and $A_2=-2.7 \times 10^{-3} \text{ m}^2 \text{s}^{-1}$. $\alpha(z)$ = thermal damping rate; N = Brunt-Väisälä frequency; k_i = the zonal wavenumber; $\bar{u}$ = the zonal wind.

In our sensitivity study of the QBO period to wave forcing, the phase speeds are not changed. We tune the total wave forcing $F(z)$ on the QBO in our model by varying the parameters ' A_i ' in equations by a constant factor (see Table 1) from their baseline values.

The result is shown in Figure 6. As predicted by Plumb (1977), the QBO period decreases (increases) as we increase (decrease) F from our baseline case of SC-mean (Case (b)). For a value of F that yields a mean QBO period of 24, 30 or 36 months, non-stationary behavior disappears, because now the intrinsic period is synchronized with the SAO period, being an integer multiple of the latter's period. Non-stationary behavior returns when the magnitude of F lies between and away from these values.

5. Conclusions

Using ERA-40 data, which extends to the stratopause region and encompasses both the SAO and QBO, we find that the period of the QBO is always an integer multiple of the SAO period. The westerly phase of a QBO always corresponds to a westerly SAO above. A plausible explanation is provided. Although a SAO is not “absolutely necessary” for seeding the QBO below, the westerly SAO facilitates the initiation of the QBO’s westerly phase. Since the equatorial upper stratosphere has an easterly bias in the absence of the SAO, as it should by angular momentum considerations in an eastward rotating planet, the initiation of the westerly phase of the QBO would have become more difficult in the absence of the SAO and thus would have occurred higher up in the mesosphere than observed. We have also shown that since there is very little variation of the QBO period in the vertical (within limits of about 1 to 2 months), the same synchronization with the SAO should also hold throughout the stratosphere.

A second interesting feature of the observed behavior of the QBO period is that it jumps from 4-SAO periods to 5-SAO periods and back in a seemingly random way. This non-stationary behavior is explained using a model. In our model we show that the non-stationarity is not due to the fact that the solar-cycle forcing is time-varying, because the same behavior remains when we remove the solar cycle in our perpetual SC-mean run (see comparison between Figure 3 and 5). An alternative explanation is based on the fact that the magnitude of wave forcing in our current climate lies in the parameter range between 4-SAO and 5-SAO. Therefore the period of the QBO determined by its internal forcing mechanism is incompatible with the SAO period above. To maintain synchronization with the SAO period, the QBO period jumps in a non-stationary way so that a long-term average of its period is compatible with its intrinsic wave forcing. If this explanation is correct, then we should be able to find a different behavior for a different wave forcing, larger or smaller

than the value for the current climate, for which the intrinsic period is an integer multiple of the SAO period. Under such a condition, the non-stationary behavior should disappear. This is indeed the case, and the QBO period locks into 4- (or 5- SAO) periods, when the relative forcing is increased (or decreased) by $\sim 10\%$. (See Figure 6)

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Phase speed	Kelvin wave	Rossby-Gravity wave
$c \text{ (m s}^{-1}\text{)}$	25	-30
Case	$A_1 / (A_1)_{\text{baseline}}$	$A_2 / (A_2)_{\text{baseline}}$
(a)	1	1.1
(b)	1	1
(c)	0.91	1
(d)	0.83	1.05

Table 1. Parameters used to force the QBO in the THINAIR model.

Figure Captions

Figure 1. Height-time cross-section of the monthly mean ERA-40 zonal mean zonal wind. The top two panels are the “raw” data, while the last two panels are obtained by replacing the data in the 1-3 hPa region with the climatological seasonal cycle.

Figure 2. QBO period in ERA-40 data at 5 hPa (a) QBO period counted in units of SAO period (left scale). The solid curve at the bottom is the solar cycle index ($W\ m^{-2}$) (right scale). (b) The histogram of the QBO period, counting the number of occurrences when the QBO period is 4-SAO periods and when it is 5-SAO periods. (c) The QBO period as a function of pressure level. (*) represents the QBO during 1997, (+) represents the QBO during 1962, and diamond represents the mean QBO periods.

Figure 3. Height-time cross-section of zonal mean zonal wind for the SC-varying model case.

Figure 4. Same as Figure 2 but from model results for the SC-varying case. The solid curve is the solar index as Figure 2 but repeated from 1964 to 1995 to cover 400 years. Here we show a subsegment of 46 years out of the 00 year run. In figure (c) (*) represents the QBO during year 162 and (+) represents the QBO during year 128. Diamond represents the mean QBO periods during these 46 years.

Figure 5. Height-time cross-section of zonal mean zonal wind for SC-mean case

Figure 6. The histogram of the periods of the QBO for different wave forcings. See Table 1 for details; case (b) is the baseline case, same as in Figure 5.

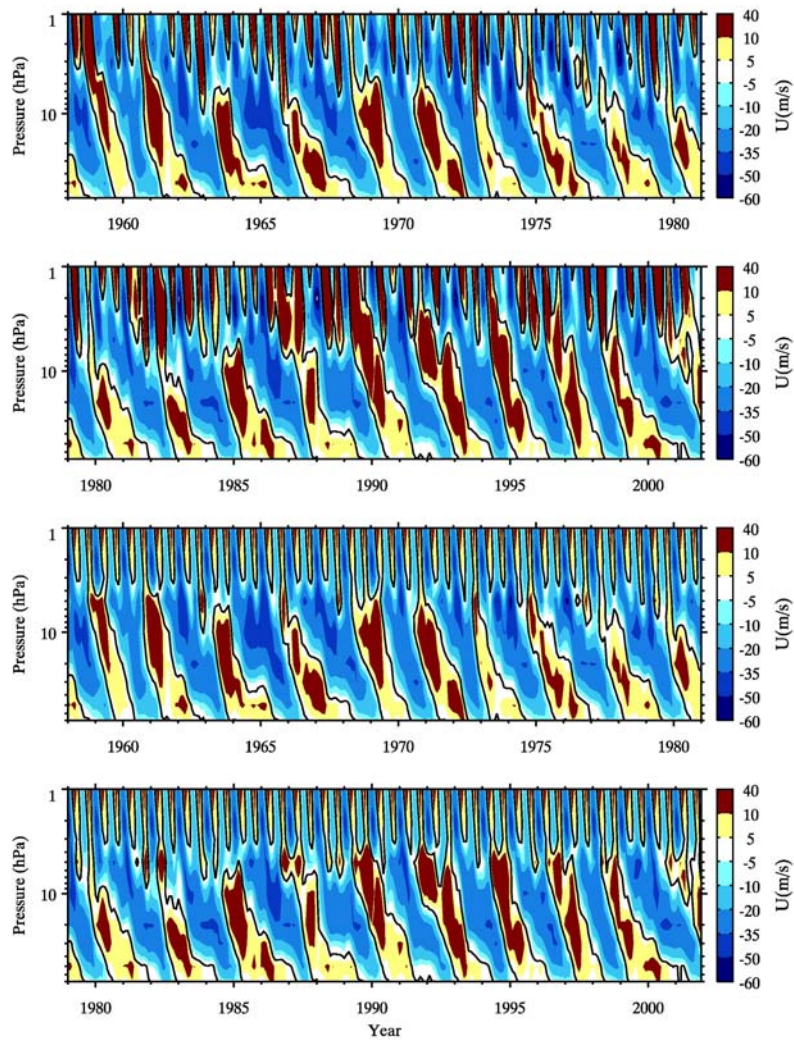


Figure 1. Height-time cross-section of the monthly mean ERA-40 zonal mean zonal wind (top two panels). In the lower two panels, the zonal wind in the upper three levels are replaced by its seasonal climatology, which removes the QBO and shows the SAO more clearly..

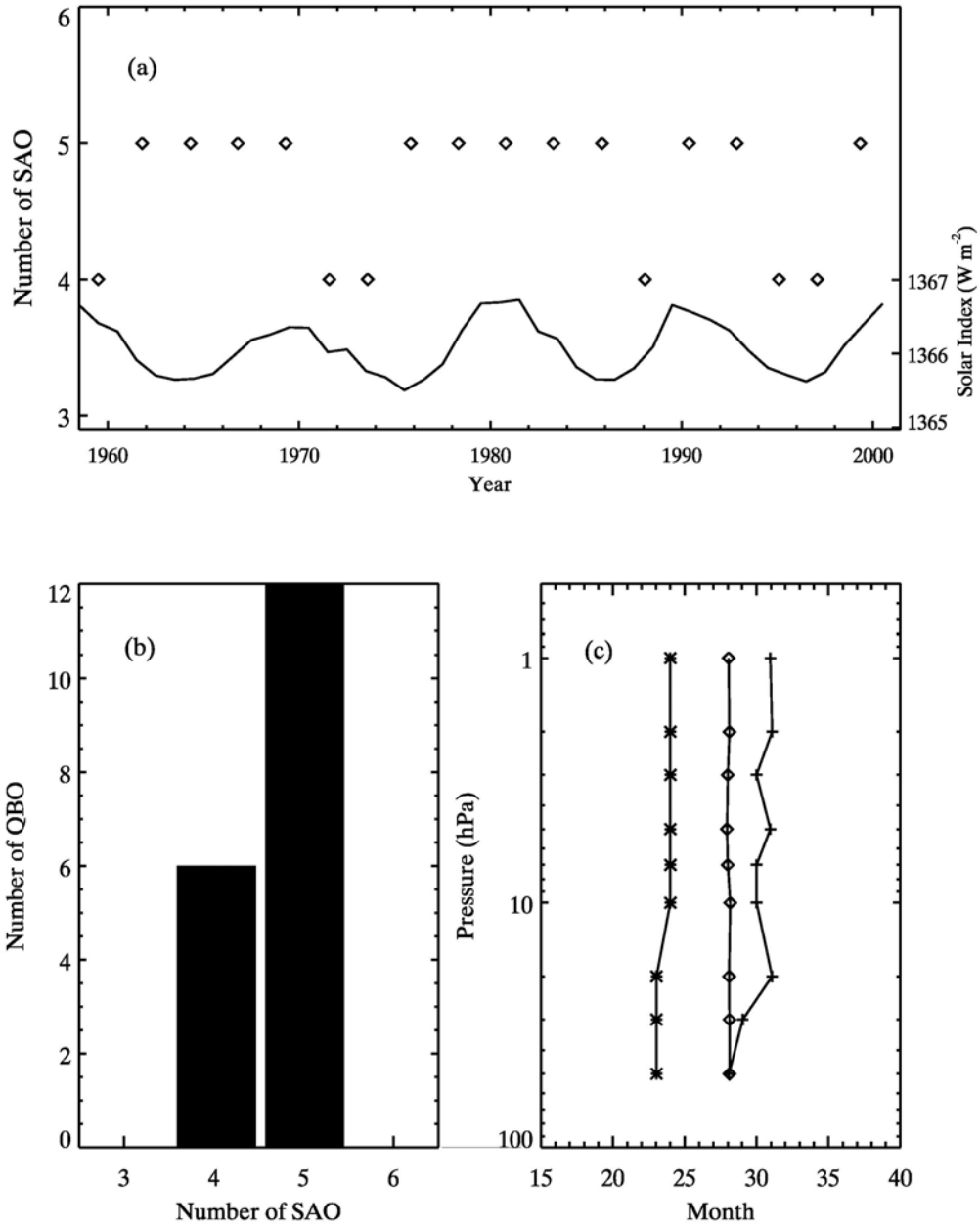


Figure 2. QBO period in ERA-40 data at 5 hPa. (a) QBO period counted in units of SAO period (left scale). The solid curve at the bottom is the solar cycle index (W m^{-2}) (right scale). (b) The histogram of the QBO period, counting the number of occurrences when the QBO period is 4-SAO

period and when it is 5-SAO period. (c) The average QBO period as a function of pressure level, along with the standard deviation (± 1 sigma). The QBO period in (c) is calculated objectively in months using the zero crossings of the zonal wind.

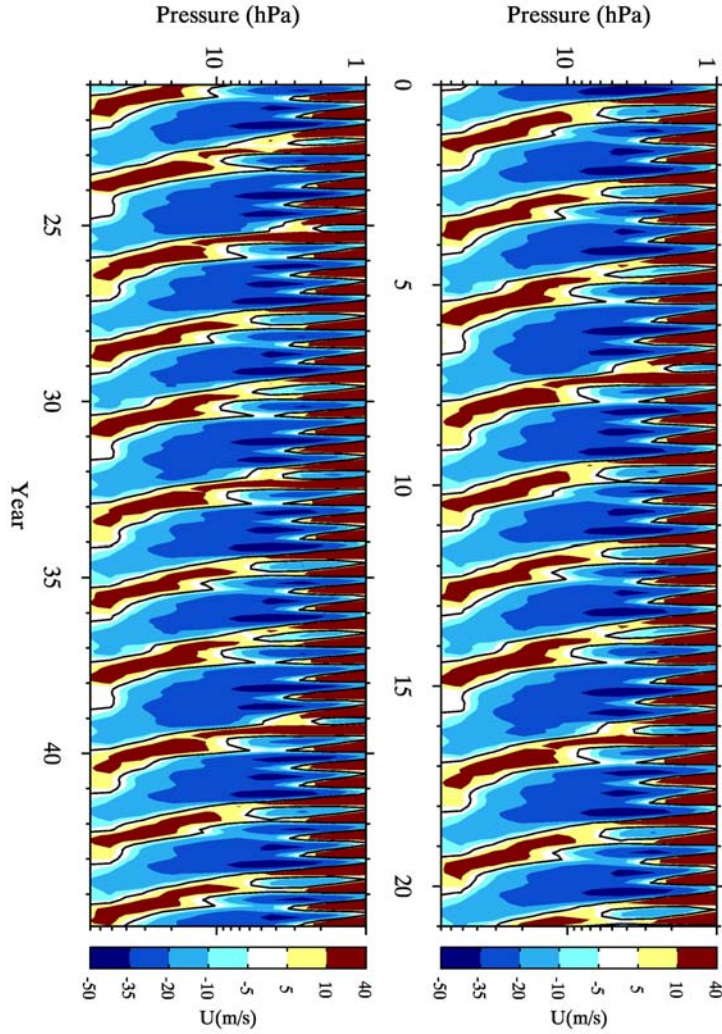


Figure 3. Height-time cross-section of zonal mean zonal wind for SC-varying case

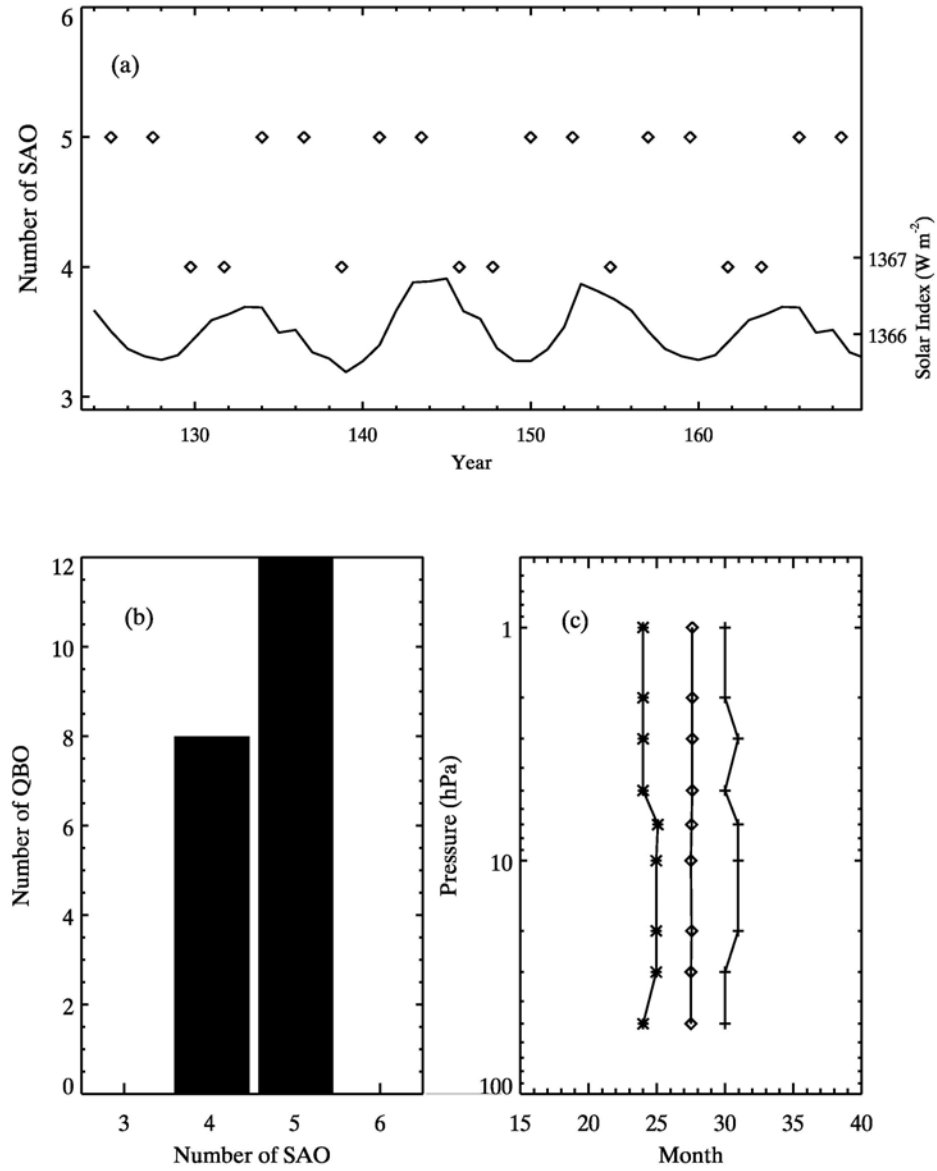


Figure 4. Same as Figure 2 but from model results for the SC-varying case. The solid curve is the solar index as Figure 2 but repeating the data from 1964 to 1995 to cover 400 years. Here we choose 46 year out of 400 year run from 126 to 172. In figure (c) (*) represents the QBO in year 162 and (+) represents the QBO year 128. Diamond represents the mean QBO periods during these 46 years

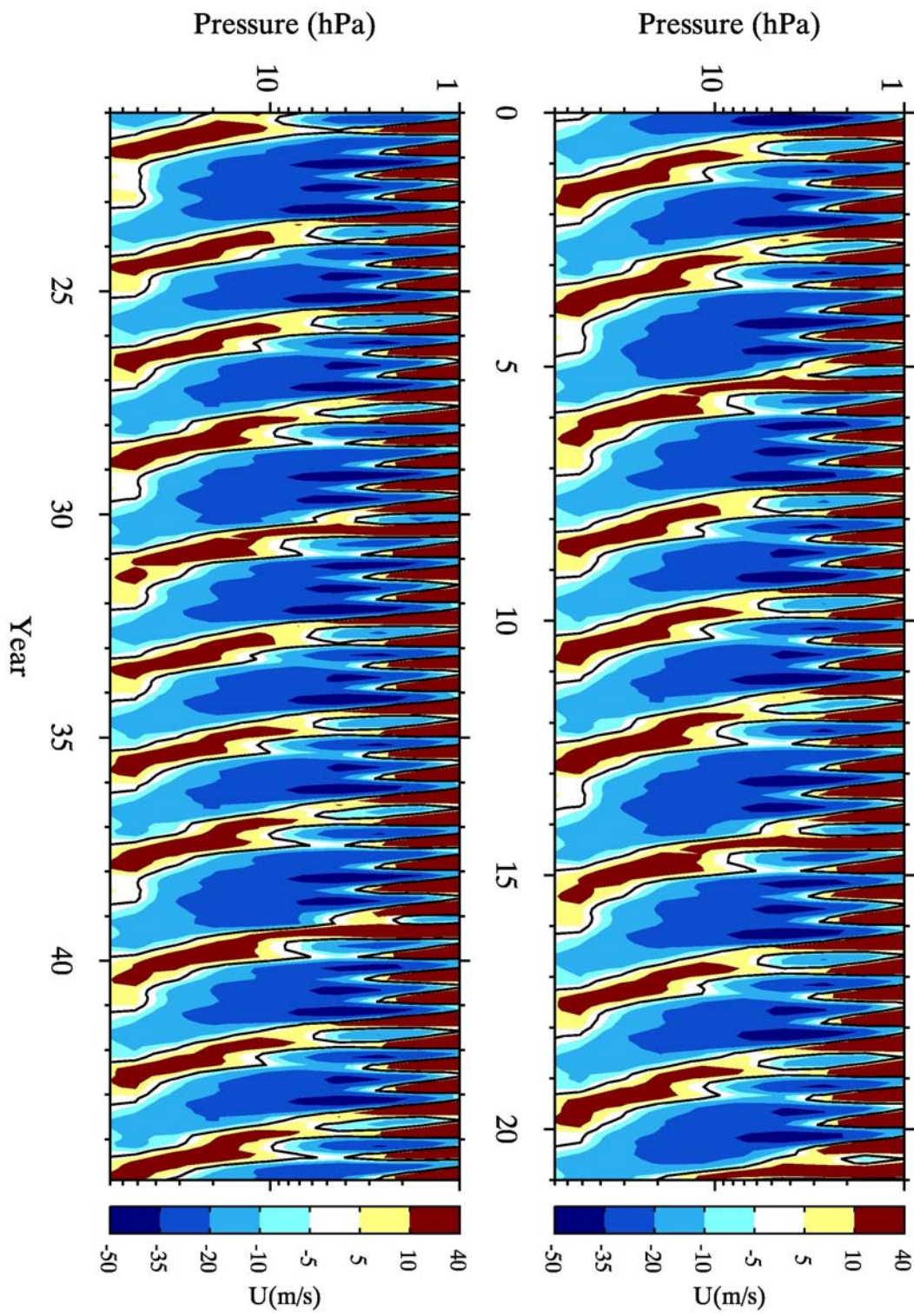


Figure 5. Height-time cross-section of zonal mean zonal wind for SC-mean case

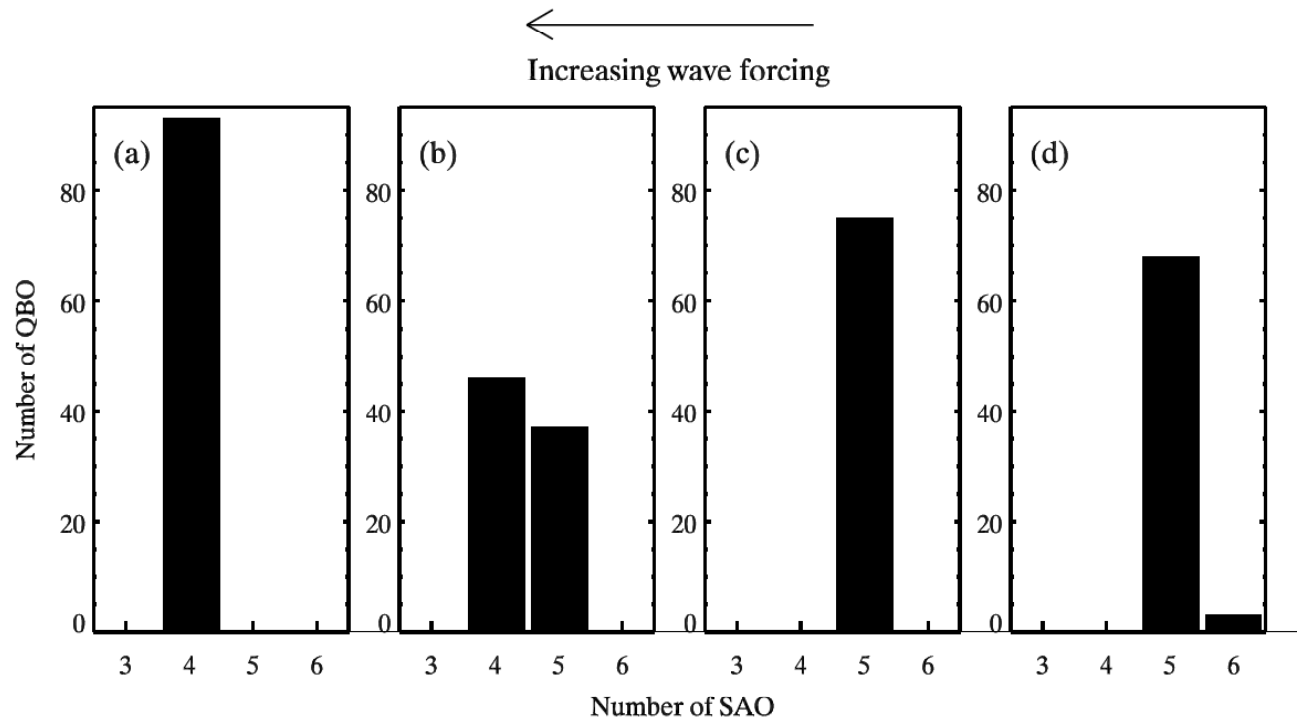


Figure 6. The histogram of the periods of the QBO for different wave forcings. See Table 1 for details; case (b) is the baseline case, same as in Figure 5.