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A reexamination of the QBO period modulation by the solar cycle

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[1] Using the updated Singapore wind from 1953 to 2007 for the lower stratosphere 70–10 hPa, courtesy of Barbara Naujokat of Free University of Berlin, we examine the variation of the period of the Quasi-Biennial Oscillation (QBO) as a function of height and its modulation in time by the 11-year solar cycle. The analysis is supplemented by the ERA-40 reanalysis up to 1 hPa. Previously, it was reported that the descent of the easterly shear zone tends to stall near 30 hPa during solar minimum, leading to a lengthened QBO westerly duration near 44–50 hPa and the reported anticorrelation of the westerly duration and the solar cycle. Using an objective method, continuous wavelet transform (CWT), for the determination of local QBO period, we find that the whole QBO period is almost invariant with respect to height, so that the stalling mechanism affects only the partition of the whole period between easterly and westerly durations. Using this longest data set available for equatorial stratospheric wind, which spans five and half solar cycles (six solar minima), we find that in three solar minima, the QBO period is lengthened, while in the remaining almost three solar cycles, the QBO period is lengthened instead at solar maxima. We suggest that the decadal variation of the QBO period originates in the upper stratosphere, where the solar-ozone radiative influence is strong. The solar modulation of the QBO period is found to be nonstationary; the averaged effect cannot be determined unless the data record is much longer. In shorter records, the correlation can change sign, as we have found in segments of the longest record available, with or without lag.

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1. Introduction

[2] The Quasi-Biennial Oscillation (QBO) is a dominant oscillation of the equatorial stratospheric zonal wind, whose period is irregular but averages to about 28 months. The classical mechanism of QBO [*Holton and Lindzen*, 1972; *Lindzen and Holton*, 1968] attributes the period of the QBO to internal interactions between the waves and the mean flow in the equatorial stratosphere. Later modifications to the theory take into account the QBO's secondary circulation [*Plumb and Bell*, 1982] and the upwelling branch at the equator of the Brewer-Dobson circulation in affecting the descent rate and hence the period [*Baldwin et al.*, 2001; *Kinnersley and Pawson*, 1996].

[3] Whether the QBO's period is affected by external forcing, such as the 11-year variation in the solar radiation (especially its variation in the UV component), is an intriguing open question. *Quiroz* [1981], using 12-month running mean of the Balboa data (9.0N, 79.6W), was the first to point out that there is a decadal variation in the QBO's period. *Salby and Callaghan* [2000] found, using radiosonde data near the equator at 45 hPa from 1956 to 1996 (from Free University of Berlin), that the duration of the westerly phase varies on a decadal cycle from 12 months to 23 months, being longer during solar minimum and shorter during solar maximum. The easterly phase at that level, on the other hand, seems to be always about 12 months long in duration. The authors suggested that easterlies near 30 hPa tend to stall during solar min instead of descending and replacing the westerlies below, thus prolonging the westerly phase near 45 hPa.

[4] The descent of the easterlies tends to stall more easily than that of the westerlies because the QBO's self-induced secondary circulation is upward for easterly momentum acceleration [*Plumb and Bell*, 1982]. Slowing down the descent of both the easterly and westerly phases near the equator is the upward branch of the Brewer-Dobson circulation, which however is stronger during the easterly phase of the QBO. The Brewer-Dobson circulation is remotely forced by planetary wave breaking and dissipation in the polar stratosphere [*Holton et al.*, 1995; *Randel et al.*, 2002; *Hood and Soukharev*, 2003]. This is consistent with the finding of *Dunkerton* [1990] that this stalling almost always occurs during Northern Hemisphere winter, when the planetary wave dissipation is the strongest. It has been long suggested [*Labitzke*, 1982] that more Stratospheric Sudden Warmings (SSWs) occur in late winter in Northern Hemisphere during solar max than during solar min. This result

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has recently been established statistically by *Camp and Tung* [2007]. Since SSWs produce downwelling at the pole and upwelling at the equator, it would seem more plausible that the stalling of the descent of the QBO in the equatorial region should occur during solar max instead of the solar min, at least in late winter, unless the proposed stalling mechanism is not the dominant factor in controlling the QBO period. *Kodera and Kuroda* [2002], on the other hand, presented data which showed that the upwelling branch in the subtropics of the Brewer-Dobson circulation is weakened during solar max. No data is shown equatorward of 20 degrees of latitude and below 10 hPa, a region of interest for the equatorial QBO. Furthermore, their composite uses only two solar cycles, from 1979 to 1998, during which two volcano eruptions occurred (El Chichon and Pinatubo).

[5] *Soukharev and Hood* [2001] confirmed the conclusion of *Salby and Callaghan* [2000] using a composite analysis of the band-pass filtered 10 to 70 hPa equatorial zonal wind for the period from January 1957 to December 1999 (from Free University of Berlin). For each solar maximum (and for each solar minimum), two westerly and two easterly phases of the equatorial zonal wind were composited after alignment. The eight westerly or easterly phases of the zonal wind were aligned in such a way that the zero-wind lines all start at 10 hPa in month zero. They found that the westerly phase in the lower stratosphere tend to last longer at solar minimum than at solar maximum, with the largest difference observed at the 40–50 hPa levels.

[6] *Gabis and Troshichev* [2006] pointed out that their data analysis is not consistent with the implicit assumption of *Soukharev and Hood* [2001] and *Salby and Callaghan* [2000] that there are more stalling of the easterlies and the prolongation of the westerlies in years of solar minimum since almost half of all short QBO durations occur near solar minima (1962, 1974, 1996 and 1998).

[7] There are other questions that remain unanswered. For example, if stalling of the easterlies at 30 hPa is the relevant mechanism for the prolonged duration of the westerly phase below, should one expect the period of the QBO to be different above and below 30 hPa? When the duration of the westerly phase is prolonged, does the duration of the easterly phase become shortened so that the period of the QBO itself is unchanged? In the GCM model experiment of *Palmer and Gray* [2005] both the easterly duration and the westerly duration are shortened during solar max, in contrast to the 2-D model of *McCormack* [2003], where as westerly is shortened, easterly is lengthened, during solar max.

[8] *Hamilton* [2002] examined a longer equatorial record (than *Salby and Callaghan* [2000]) from 1953 to 2001, also from Free University of Berlin. He found that while the correlation with the solar flux and the westerly duration is −0.46 over the 17 westerly phases during the 1956–1996 period studied by *Salby and Callaghan* [2000], the correlation falls to an insignificant −0.10 when computed over the 22 westerly phases in the longer record. In particular Hamilton pointed out that toward the end of his record in the 21st century, the relationship discovered by Salby and Callaghan appears to fail. It would be interesting to examine a longer data record further into the 21st century, when the stratosphere is not known to be contaminated by a major volcanic eruption. The eruption of Pinatubo in 1991 was cited as a possible reason for some of the problems with the correlation of *Salby and Callaghan* [2000] in the early 1990s.

[9] Using 44 years of ERA-40 data from January 1958 to December 2001, spanning 18.5 QBO cycles, *Pascoe et al.* [2005] arrived at a conclusion consistent with that of *Salby and Callaghan* [2000] and *Soukharev and Hood* [2001]. They found that the mean time for the easterly shear zone to descend from 20 to 44 hPa is 2 months less under solar max conditions than under solar min conditions. This rapid descent of the easterly shear zone cuts short the westerly pase of QBO in the lower stratosphere during solar max periods. In particular the authors found that a Spearson's rank correlation with the solar radio flux of the easterly descent rate for the period from 1958 to 1990 is a rather high 0.84 at 14 month lag. However, they also pointed out that the correlation breaks down during the 1990s, but they attributed the anomalous climate of the tropical atmosphere after the eruption of Pinatubo in June 1991 for this breakdown. This explanation can possibly be ruled out if we extend the data to 2007, since volcanic aerosols stay in the stratosphere most likely not longer than 3 years. Most of the radiative effects by volcanic aerosols are from sulphate aerosols formed as a result of oxidation of the sulphate gas emitted by explosive volcanic eruptions into the stratosphere. The sedimentation e-folding time for sulphate aerosols is typically about 1 year [*Lambert et al.*, 1993], while most of the other ash particulates sediment out of the stratosphere within 3 months. *Ramaswamy et al.* [2001] in the IPCC 3rd Assessment Report and *Forster et al.* [2007] in the 4th Assessment Report commented that the stratosphere is now the cleanest since the satellite era.

[10] In this work, we shall reexamine the possibility of a decadal solar cycle modulation of the period of the QBO using an objective method and the longest record available. It is the same in situ data set of near equatorial wind at 50 hPa that *Hamilton* [2002] used, distributed by the Stratospheric Research Group at the Free University of Berlin (FUB), here updated by B. Naujokat to span from 1953 to 2007. Figure 1 shows the time-height cross section of the FUB wind. It shows the descent of the easterly shear zone to have more interannual variability compared with that of the westerly shear zone, as pointed out by previous authors. In this extended record, the stalling of the easterlies and the subsequent prolongation of the duration of the westerlies occurred irregularly: under solar min conditions of 1964, 1977 and 1987, but also under solar max conditions of 1967 and 2000. The corresponding time-height cross section of the ERA-40 data is given by *Pascoe et al.* [2005], and no update is available. Figure 2 shows this 40-year record up to 1 hPa in a time-height cross section. The extended height coverage shows the transition of the Semiannual Oscillation (SAO) near the stratopause into the QBO below, and the tendency of synchronization of certain westerly phases of the two phenomena, as the QBO always starts in a westerly SAO and ends when another SAO (several SAO periods later) descends into the QBO altitude. As the QBO descends into the mid and lower stratosphere, there are large (up to 12 month) changes in its easterly and westerly durations, but the whole QBO period appears to be within 1 to 2 months of its value in the upper stratosphere. These features of the QBO will be demonstrated more clearly

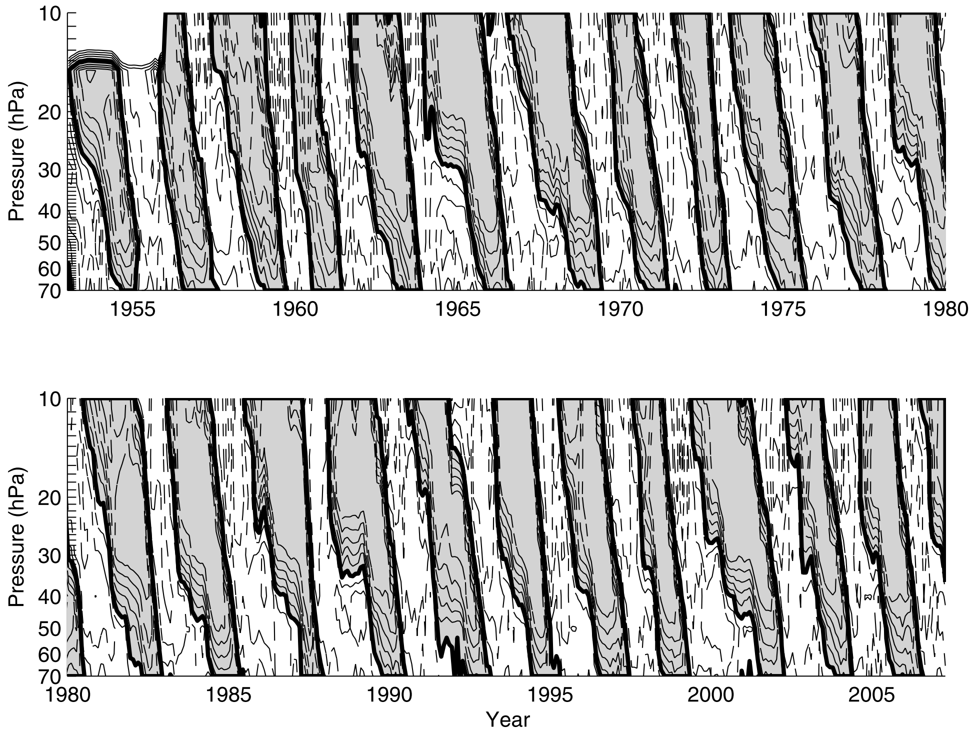

Figure 1. Time-height section of the FUB zonal wind. Easterlies are shown shaded. Contour increment is 5 m s^{-1}.

later in this paper. They impose a constraint on the possible mechanism(s) responsible for the decadal variation of the QBO period. For example, since the radiative heating by the volcanic aerosols is not expected to be vertically uniform through-out the stratosphere, it cannot be responsible for the vertically uniform part of decadal variation of the QBO period. Its effect on the QBO period is then seen to be at most 2 months, the maximum extent of the vertical variation in period.

2. Methods

[11] We use both an objective method and a subjective method for determining the QBO period, each having its own advantages and disadvantages. Calculating the period of the QBO has been a subjective procedure. It has usually involved visually determining when a descending westerly (or easterly) first crosses zero at a particular level and when it later goes back above zero. Such a procedure is sensitive to calibration errors and monthly averaging. At the lower levels, such as 70 hPa, the presence of higher-frequency zero crossings renders this subjective method less useful, as there are many zero crossings in sub QBO periods. At the upper levels, at 7 hPa and above, the method also fails because of the simultaneous presence of SAO and QBO. The use of continuous wavelet transform, which can determine the local intrinsic period of an oscillation, gives a more objective method that is not sensitive to the location of the zero-wind line. With this method the QBO period can be determined from 70 hPa to 1 hPa. However, this method does not separately determine the westerly and the easterly parts of the QBO period; for that we still need to rely on the traditional subjective methods. Most of our results do not depend critically on the use of the CWT method, and can be reproduced, but with some ambiguity, by some subjective methods, except in the upper stratosphere. The mathematical details of the CWT method are discussed in Appendix A.

[12] Note that because of the continuous nature of the CWT method, the period thus determined varies smoothly, and does not show, for example, the discrete jump from 24 months to 30 months in the QBO period sometimes seen in the raw data. What is seen in the CWT result should be interpreted as some running average of neighboring periods.

3. Results and Discussion

3.1. QBO Period Variation

[13] Figure 3 shows the local period of the QBO oscillation as determined by applying the CWT to the FUB data at 50 hPa for the period 1953–2007. This radiosonde data set of near equatorial zonal wind consists of observations at Canton Island (January 1953 to August 1967), Gan, Maldives (September 1967 to December 1975) and Singapore (since January 1976). It is the extended version of that used by *Salby and Callaghan* [2000] and *Hamilton* [2002]. It shows decadal variations around the mean period of 28 months. Because of this variation of periods, a Fourier analysis would give a broad spectrum of QBO period but is unable to locate the times with long or short periods. The color scheme in Figure 3 shows the amplitude of the wavelet coefficients, with darker color indicating higher amplitudes. There is a decadal amplitude modulation of the QBO, which will be the subject of a separate paper. Here we focus on the frequency modulation. The maximum amplitude of these wavelet coefficients is marked with a dashed line in Figure 3. This marks the dominant period of the equatorial

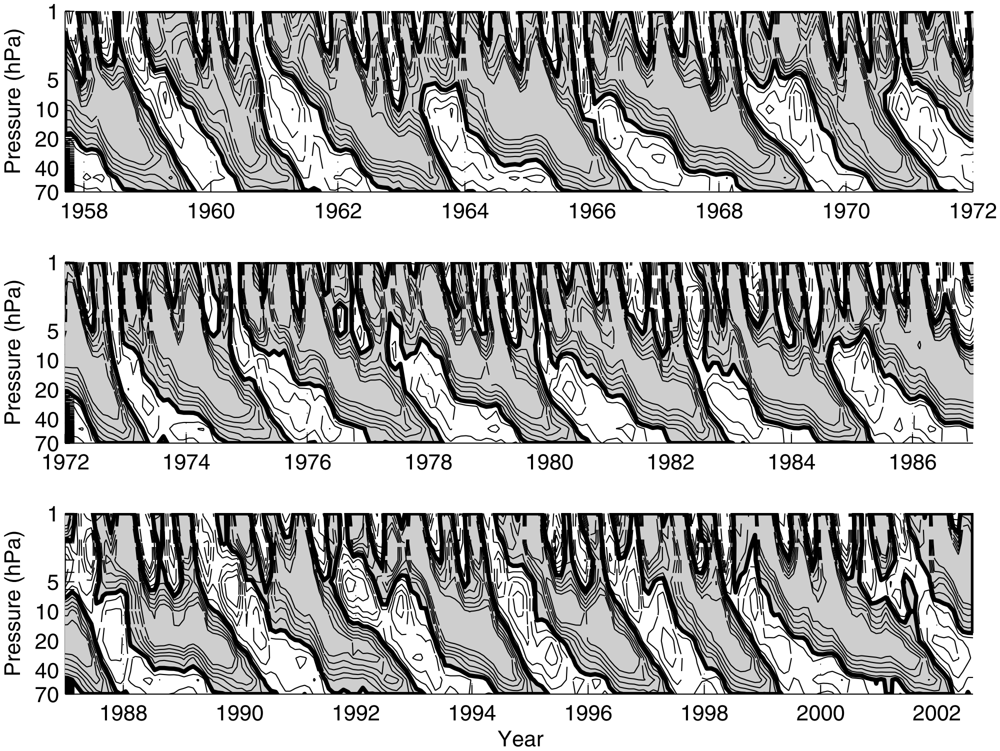

Figure 2. Time-height section of the monthly mean ERA-40 zonal wind, maintained at European Centre for Medium-Range Weather Forecasting. Easterlies are shown shaded. Contour increment is 5 m s^{-1}.

zonal wind, i.e., the period associated with the most amplitude (or kinetic energy). This is the period we will be focusing on. Below it we also plot the sunspot number as a function of years, which is used as a proxy for the 11-year solar cycle flux.

[14] Figure 3 shows that, consistent with *Salby and Callaghan* [2000], the period of the QBO reaches its maximum during the solar min of 1965, when the dominant period is 33 months, the solar min of 1976, when the dominant period is 30 months, and the solar min of 1986, when the dominant period is 31 months. Other than these three solar minima mentioned by *Salby and Callaghan* [2000], however, the anticorrelation with the solar cycle breaks down. In the solar min of 1997, the dominant QBO period reaches a low of close to 25 months, consistent instead with the finding of *Hamilton* [2002]. Going forward in time, the correlation is the reverse of that of *Salby and Callaghan* [2000]. That is, during solar max, the QBO period is longer, while during solar min the QBO period is shorter. The in-phase relationship appears to commence around 1991, and probably as early as the late 1970 if one considers relative variations (see Figure 4 later). Prior to 1960 (from 1955 to 1960), the period variation is also approximately in-phase with the solar cycle, as Hamilton already pointed out. Over the almost 6 cycles spanned by the FUB data, three cycles show anticorrelation of QBO period with solar flux, while the other two and a half cycles show in-phase correlation. As a consequence, the correlation coefficient between the two is close to zero (−0.03) for the long record of 1953–2007. It is intriguing to note the alternate correlation and anticorrelation of the QBO period with the solar cycle, which is a different behavior than two curves not related to each other at all that could also give a zero correlation coefficient. The calculation is repeated with the ERA-40 data. The result is very close to what we have shown here using the FUB data for the period of overlap.

[15] This CWT procedure is repeated for all levels of the FUB data and the result is plotted in Figure 4. It shows the same prominent decadal variation at all levels and that the differences are small with respect to height. Minor differences of about a month in period exist at the higher levels (20 and 15 hPa) and at 70 hPa prior to 1958. *Gabis and Troshichev* [2005] previously demonstrated the constancy of the QBO period with height, but only in an average for the period of 1953–2003 [see *Gabis and Troshichev*, 2005, Figure 2c]. Here we showed that this is true locally at each time in the record.

[16] Since this plot uses an enlarged scale for the QBO period, it shows the variation of the period during 1980s and 1990s better than in Figure 3. The almost in-phase relationship between the relative QBO period variation and the solar index appears as early as late 1970s and lasts till the end of the record in 2007, although in the 1980s and 1990s, the QBO variation appears to lead the solar index variation.

[17] While the period variation of the QBO is almost the same at all heights in the lower stratosphere, above 30 hPa it is the easterly period variation that is responsible for most of the variation of the whole QBO period, but below 30 hPa it is the westerly period that controls the whole QBO period variation. Figure 5 shows that, interestingly, the easterly period at 15 hPa and the westerly period at 50 hPa vary synchronously. The amplitude of the variation is also about

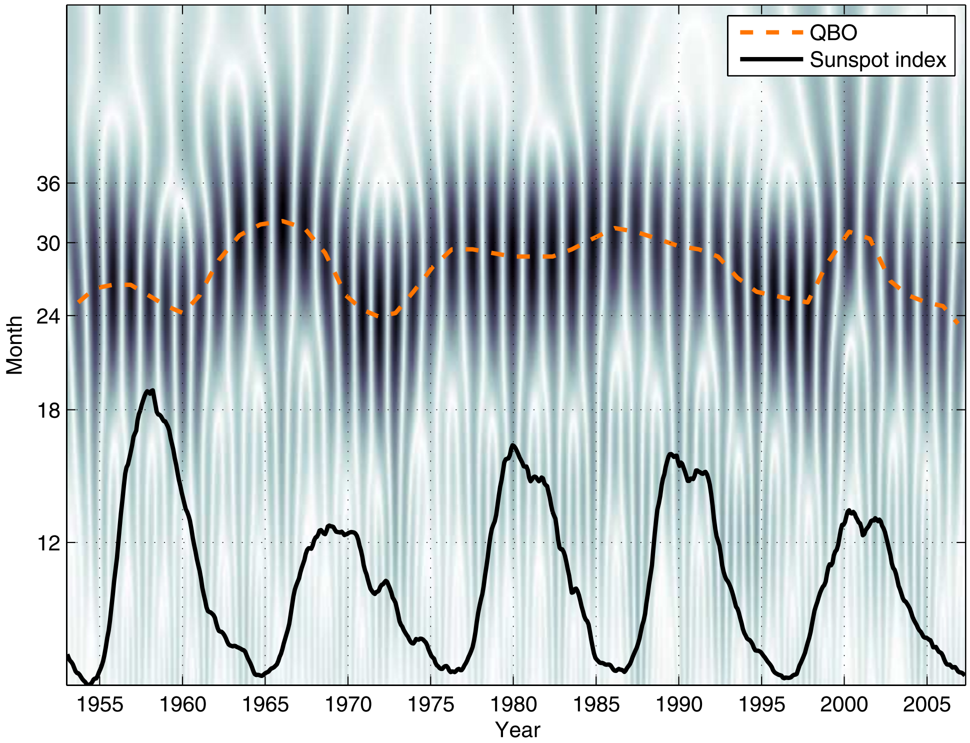

Figure 3. Local period in months of the 50 hPa FUB wind as determined by the CWT. The darker region denotes location of higher amplitude of the zonal wind. The dashed line traces the location of the maximum amplitude. Superimposed, in solid line, is the sunspot number (monthly averaged), which is a proxy for the solar cycle radiative flux variability.

the same, from 12 to 23 months. This observational result can be understood as follows. When the mean equatorial upwelling is strong it slows down the descent of the easterlies. The effect being more noticeable on the easterlies than on the westerlies as explained in the Introduction. Because the descent of the QBO east phase is preferentially stalled near the 30 hPa level in NH winter-spring, the duration of the easterly QBO phase is typically longer than the westerly phase above this level while the reverse is true below this level. This description explains the differing behavior of easterlies and westerlies above and below the stalling level, while the whole period of the QBO remains the same at these levels. Mechanistically, the upward propagating gravity waves and equatorial waves that are responsible for inducing the descent of the easterlies and westerlies need to pass through the region at 50 hPa of a prolonged duration of westerlies. The filtering effect by the lower stratospheric westerlies means that there is no deposition of westerly wave momentum above this level. As a result, the easterly duration is prolonged at 15 hPa. In the upper stratosphere, the easterly phase at around 3 hPa ends when the westerly wanes in the lower stratosphere, and westerly phased gravity waves again propagate up to the upper stratosphere and initiate the next westerly descent. It is in this way that the upper level easterlies and lower level westerlies are related in their duration.

3.2. Comparison With the Subjective Methods

[18] Figure 6 (top) shows a comparison of the period as determined objectively using continuous wavelet transform and the subjectively determined period by measuring the period between successive zero crossing of the zonal wind. It turns out that the result for the QBO period obtained by the subjective method is very different depending on whether one defines the full QBO period as easterly plus westerly, or as westerly plus easterly. The easterly plus westerly period appears to have a few more oscillations in 1980–1990 than the period as determined by westerly plus easterly durations. Our method turns out to be consistent with the average of these two definitions, provided that monthly averages are used in the subjective method.

[19] In Figure 6 (bottom) the "period" of the westerly phase and that of the easterly phase are separately determined by the subjective method. These are consistent with the results of *Salby and Callaghan* [2000] and *Hamilton* [2002], but for the longer data record. It shows a decadal variation of the westerly period that tracks quite closely that of the full QBO period as determined by the continuous wavelet transform. Therefore our conclusion that there is no correlation of the QBO period with the solar cycle also applies to the westerly phase duration separately. The correlation coefficient of the westerly phase duration variation with the sunspot time series for the full period of 1953–2007 is less than −0.10, also negligible.

[20] *Hamilton and Hsieh* [2002] proposed using the circular nonlinear principal component analysis to objectively analyze and characterize the quasi-periodic QBO oscillation. They found that a single time series of the QBO phase can be found for data at all levels. Although their method is not specifically aimed at studying the

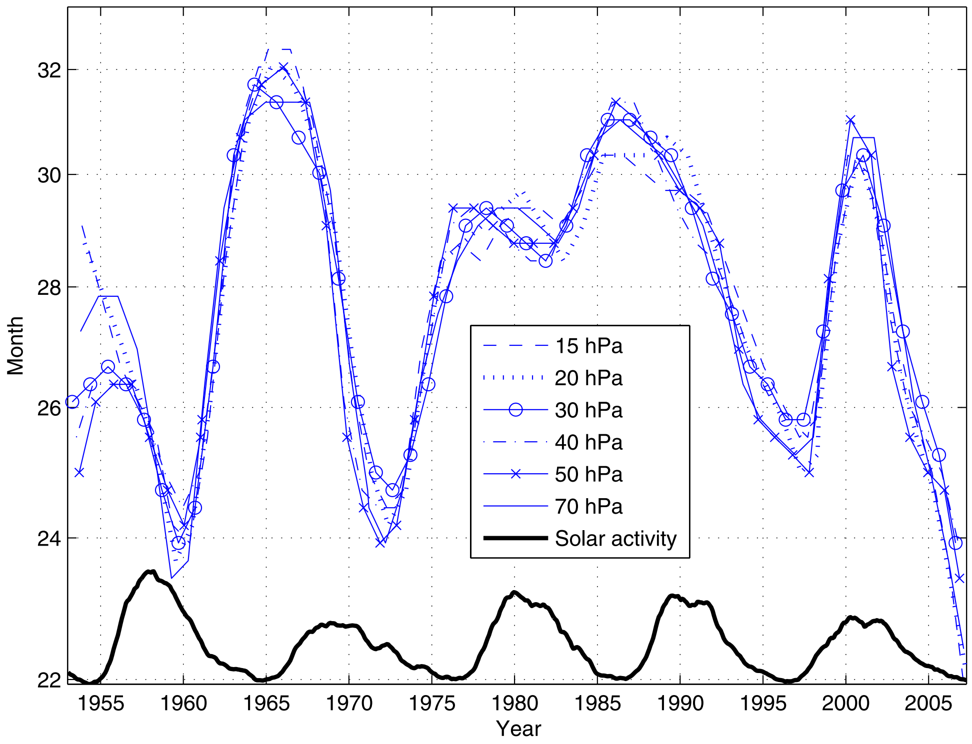

Figure 4. The QBO period as determined by the CWT method using the FUB data for various pressure levels in the lower stratosphere.

frequency variation of the QBO, a period variation similar to our CWT result was obtained by *Hamilton and Hsieh* [2002, Figure 10], but with much high-frequency irregular oscillations. *Hamilton and Hsieh* [2002] also concluded, on the basis of their shorter record, that there is "no clear connection with the 11-year solar cycle."

3.3. Behavior at Different Pressure Levels in the ERA-40 Data

[21] These CWT calculations were repeated with the ERA-40 data up to 1 hPa. (Above that level the QBO is no longer the dominant oscillation because of the presence of SAO, and the CWT method does not yield an unambig-

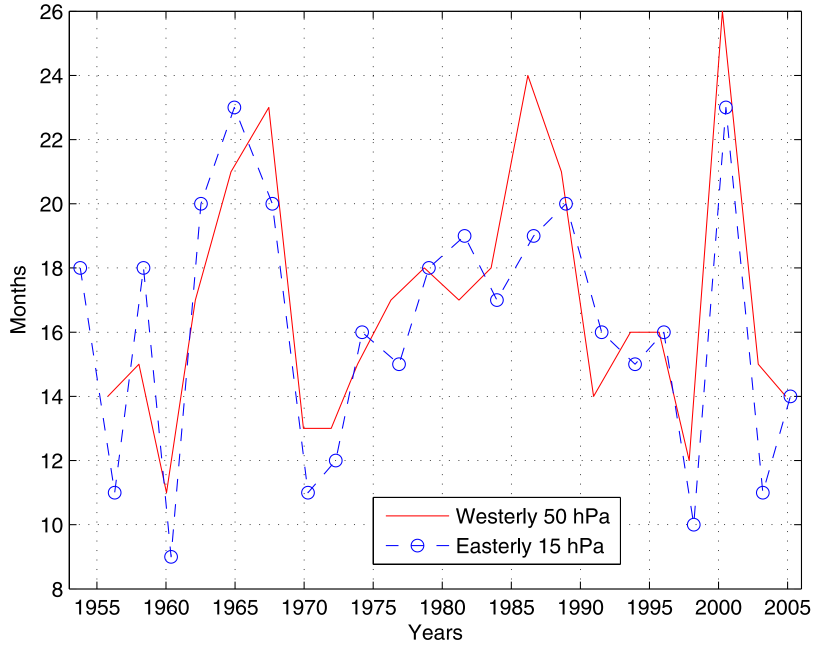

Figure 5. The period of the westerly phase at 50 hPa (in solid line) and that of the easterly phase at 15 hPa as a function of year.

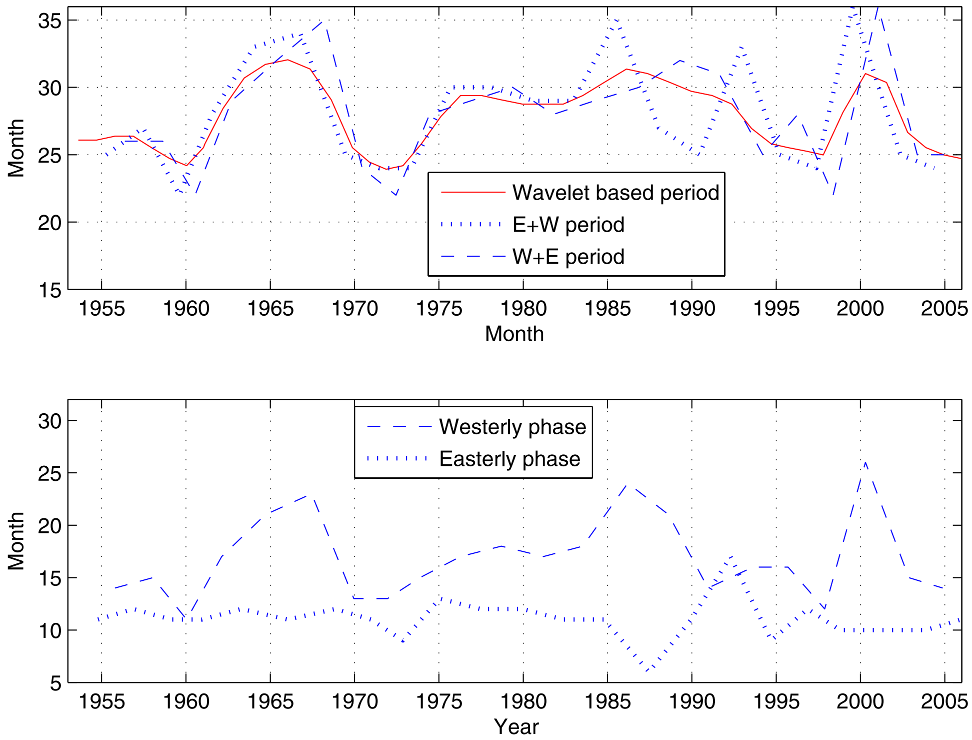

Figure 6. (top) A comparison of the QBO period as determined by the CWT method (in solid line) and that determined subjectively by adding the westerly phase period followed by the easterly phase period (in dashed line) and by adding the easterly phase period followed by the westerly phase period (in dotted line). (bottom) The westerly phase duration (in dashed line) and the easterly phase duration (in dotted line). All at 50 hPa.

uous QBO period.) The results are similar to those obtained using the FUB data for the period, except that the ERA-40 data extend to higher levels. This is shown in Figure 7. It is seen that the QBO period is almost constant in height, with the possible exception during the decade of 1980–1990, when changes of about 1 to 2 months in QBO period are seen around 20 hPa. During this period, El Chichon erupted in 1982 and Pinatubo in 1991. This implies that the influence of the volcanic aerosols on QBO period is at most 2 months. In the recent decade, when the stratosphere is clean, the QBO period is again almost independent of height, to within 1 month. This again implies that perturbations to the stratosphere, such as ENSO and SSWs, which should be nonuniform with height, are not the dominant mechanism affecting the QBO period.

[22] We show the CWT frequency-time plot at 2 hPa in Figure 8. Even at this high altitude, the QBO period and its variations are well separated (in frequency domain) from that of the SAO. The amplitude connections between SAO, the annual cycle and the QBO are seen in vertical strings of darker color, which show the sychronization of the QBO with the SAO and the annual cycle.

3.4. Lagged Correlations

[23] It has been suggested that the correlation of the westerly phase duration variation and the sunspot time series can be improved by considering lags between the two signals, and by looking at 40 hPa (L. L. Hood, personal communication, 2007). We have mentioned earlier that the QBO period is in phase with the solar cycle index in the decades of 1990s and 2000s, and also over half a cycle in the 1950s. This in-phase relationship is opposite to the behavior in the intervening three decades. This fact does not change with lagged correlation. Nevertheless, during the middle three decades considered by *Salby and Callaghan* [2000], the anticorrelation coefficient can be improved with 22-month lag. The improvement is large enough that even with the opposite phased correlation in the later decades the overall anticorrelation is improved in the extended record considered here.

[24] The time series for period durations obtained using the subjective method has only one data point for each QBO period, and needs to be interpolated for the consideration of lagged correlation. Using a piecewise cubic Hermite interpolation method, the whole QBO period time series and the westerly phase duration time series have been produced with monthly increments at 40 hPa. At this altitude, the period considered by *Salby and Callaghan* [2000], 1956–1996, yields a greatly improved anticorrelation with the solar index of −0.79 for the westerly duration at 22 month lag, while for the period 1957–1999 studied by *Soukharev and Hood* [2001] the anticorrelation of the westerly duration with solar cycle is improved to −0.74 with 22 months lag. These correlation coefficients remain significant, though smaller, at −0.64, over the extended period studied by us, while the zero-lag correlation is much smaller at −0.27.

[25] For the whole QBO period, the correlation coefficient is also improved by considering a lag, but the

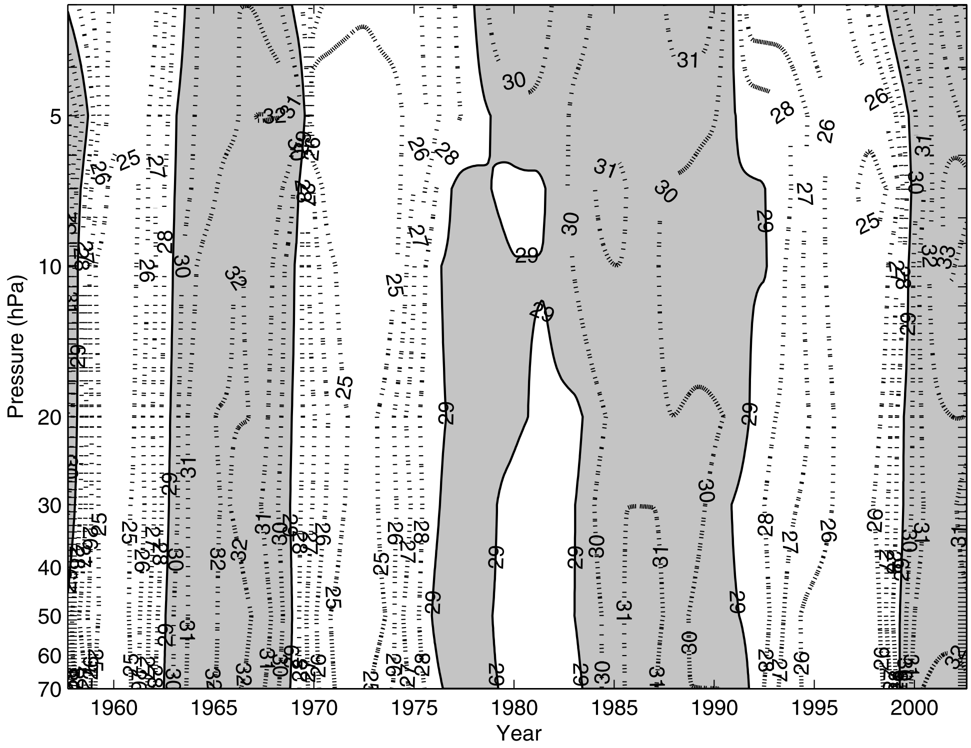

Figure 7. The QBO period as determined by the CWT method using the ERA-40 data for various pressure levels in the stratosphere. Local maxima are shown shaded. Contour increment is 1 month.

improvement is not large enough to be statistically significant. (The correlation coefficient at zero lag is roughly zero for the full QBO signal, and reaches a maximum magnitude of −0.32 with 27 month lag.)

[26] Despite this improvement in anticorrelation of the westerly duration at 40 hPa with the solar index, the fact remains that the recent decade shows opposite phased behavior than the middle three decades. This may be

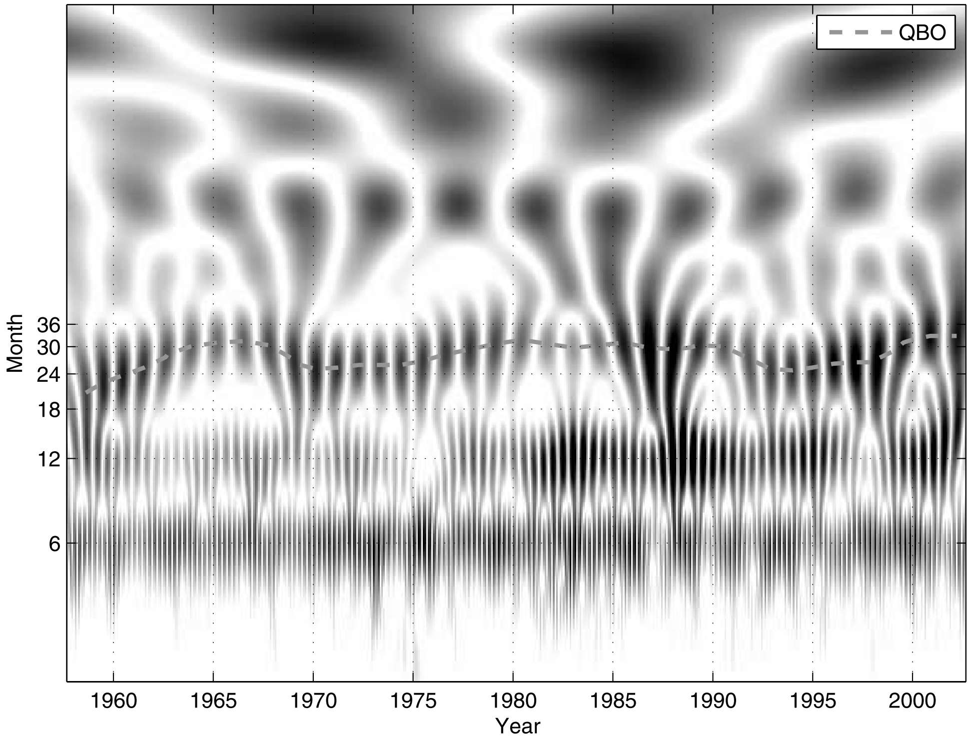

Figure 8. Same as Figure 3 except for the zonal wind at 2 hPa.

another sign that the QBO period response to solar cycle forcing may be nonstationary, and that a much longer time series than the one currently available is needed to see if the two are correlated, and to determine the sign of the correlation.

4. Conclusion

[27] Previous authors have pointed to the anticorrelation of the duration of the westerly phase of the QBO at the equator with the solar cycle in the three decades, 1960s, 1970s and 1980s, in the lower stratosphere. In particular, during the three solar minima in this period the duration of the westerly phase reaches a local maximum. In this paper an expanded study is undertaken for the longest period of record available from the Free University of Berlin, and for the levels between 70 and 15 hPa. This study is supplemented by the ERA-40 data, up to 1 hPa.

[28] We have three main results: (1) The period of the QBO is almost the same in the vertical in the stratosphere. (2) There is a decadal variation of the QBO period of up to 12 months; below 30 hPa such a variation of the whole QBO period is reflected in the variation of the westerly duration, while above 30 hPa it is the easterly duration that follows the decadal variation of the whole QBO period. (3) The decadal variation of the whole QBO period, and that of the westerly duration below 30 hPa, shows anticorrelation with the solar cycle during the middle three decades but positive correlation in the remaining decades in the 55-year record examined. This may be a sign of nonstationary behavior. These results are not entirely new, and have been mentioned by previous authors. It is now confirmed by us using the longest stratospheric record available. The synthesis of these results is discussed below.

[29] Previous attention has focused on the decadal variation of the duration of the westerly QBO at the equator in the lower stratosphere, especially at around 40–50 hPa, and pointed to the mechanism of the stalling of the descent of the easterly shear zone near 30 hPa in prolonging the westerly duration below. Our new result shows that there is the same decadal variation of the whole QBO period, and so this proposed mechanism on the descent rate of easterly shear zones, if it works, only explains the partition of the whole QBO period into the two parts: Below 30 hPa, the westerly duration is longer than the easterly duration and it is the former which contains the decadal variation in the whole QBO period. Since the same decadal variation of the whole QBO period exists throughout the stratosphere, the origin of its variability may arguably be above the level we examined, although this conclusion is only tentative until checked by a model. This is because the wave mean flow interaction in the QBO phenomenon is known to be able to transmit lower stratospheric influence to the upper levels through the filtering effect (see the discussion earlier on the effect of a prolonged westerly region in the lower stratosphere delaying the onset of the next westerly phase in the upper stratosphere). A simple possibility is the radiative perturbation by the solar max in the upper stratosphere that affects the QBO period in that photochemical region. This same decadal period variation is then preserved for all heights in the stratosphere with small variations of a month or two, much smaller than the decadal variation itself, which can be as large as 12 months. These small variations of a month or two can be caused by a number of mechanisms, such as volcanic aerosol heating, ENSO or polar stratospheric sudden warming.

[30] With respect to what the data reveals concerning the solar cycle modulation of the QBO period, we have found that in the longer equatorial zonal wind data set from Free University of Berlin (1953–2007), which spans almost six solar cycles, the conclusion is mixed. During three of the cycles the period of the QBO is anticorrelated with the solar cycle, while in the remaining almost three cycles, there is correlation with the solar cycle flux. The period previously considered by *Salby and Callaghan* [2000] contains three anticorrelated periods with one “straddling” period in 1992, which could have been discounted as due to Pinatubo. With our longer record extending into 2007, when there has not been a major volcanic eruption since 1991, it becomes more difficult to attribute the “anomalous” behavior to volcanic aerosols. We are not suggesting that there is no solar modulation of the QBO period, but the possibility exists that there is considerable unforced variability in the QBO period, so that the time series of the QBO is nonstationary even if the solar cycle forcing is held fixed, as in the model of *Mayr et al.* [2003]. This is also consistent with the suggestion of *McCormack et al.* [2007] that perhaps 150 years are needed to identify a statistically significant modulation of the QBO period in a 2-D model simulation. This possibility will be examined more in a forthcoming modeling paper.

Appendix A: Continuous Wavelet Transform

[31] We recall here only the main ideas underlying the wavelet theory and we refer to *Mallat* [1998] for a complete description. Like the complex exponential functions of the Fourier decomposition, wavelets can be used as basis functions for the representation of a signal. But, unlike the complex exponential functions, they are able to restore the temporal information as well as the frequency information. Functions depending on two real variables a and b, linked to frequency and time, respectively, are used to define the mathematical transformation:

$$WT_b^a = \int dt\, s(t)\, \psi_{a,b}(t), \tag{A1}$$

where $\psi_{a,b}(t)$ plays the same part as the exponential functions in the Fourier transform.

[32] Starting with a function ψ well localized in time and frequency spaces, a family of analyzing functions can be constructed:

$$\psi_{a,b}(t) = |a|^{-1/2}\, \psi\left(\frac{t-b}{a}\right). \tag{A2}$$

where b is a time parameter and a is analogous to a period. The initial function ψ is called the mother wavelet and has to verify the following condition:

$$\int d\xi\, \frac{|\hat{\psi}|^2}{|\xi|} = K < \infty. \tag{A3}$$

[33] This condition means that any oscillating function localized in both spaces and whose integral over the whole space $\mathbb{R}$ is null can be used as a mother wavelet. Similar to the definition of the inverse Fourier transform, it is also possible to define a reconstruction formula that allows one to rewrite $s(t)$ as an expansion on the corresponding basis. The coefficients WT_b^a defined in (A1) give a timescale representation of the initial signal allowing the detection of transient components or singularities.

[34] The results presented in this paper have been obtained using the tenth derivative of the Gaussian as a wavelet mother. Higher derivatives imply a longer support (i.e., range over a longer time window), and therefore yield a smoother result. When the support is too long, CWT begins to resemble Fourier transform and does not yield local time information anymore. The chosen wavelet mother is appropriate for the examination of decadal variation of QBO period. A link between the Fourier period and the wavelet scale can be derived analytically for each wavelet mother. The results are given here in a time-period representation rather than the usual time-frequency representation of the wavelet theory.

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