A reexamination of the QBO-period modulation by the solar cycle using continuous wavelet transform

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Using an objective method, Continuous Wavelet Transform (CWT), for the determination of local QBO (Quasi-Biennial Oscillation) period, we re-examine the previous finding that the period of the QBO in the lower stratosphere is longer during solar minima. Using the longest dataset available for equatorial stratospheric wind from Free University of Berlin, which span five and half solar cycles (six solar minima) from 1953 to 2005, we find an almost zero correlation coefficient between the solar cycle and the QBO period, thus strengthening the previous conclusion of Hamilton. In three solar minima, the QBO period is increased, while in the remaining almost three solar cycles (with no major volcanic perturbations), the QBO period increases at solar maxima. In addition, we find that the result is independent of height in the lower stratosphere.

1. Introduction

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]. 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), seemed to be the first to point out that there is a decadal variation in the QBO's period. In an important recent paper, *Salby and Callaghan* [2000] thought that the 12-month running mean may obscure the different variations in period between the westerly and the easterly phases of the QBO. Using radiosonde data near the equator at 45 hPa from 1956-1996 (from Free University of Berlin), they found that the period 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, on the other hand, seems to be always about 12 months long in duration. The authors noticed 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. The descent of the easterlies tends to stall more easily 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. The Brewer-Dobson circulation is remotely forced by planetary-wave breaking and dissipation in the polar stratosphere [*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 occur in late winter in Northern Hemisphere during solar max than during solar min. This result 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. There are other questions that also remain unanswered. For example, if stalling of the easterlies at 30 hPa is the relevant mechanism for the prolonged period of the westerly phase below, should one expect the period of the QBO to be different above and below 30 hPa? When the period of the westerly phase is prolonged, does the period of the easterly phase become shortened so that the period of the QBO itself is unchanged? The result of Salby and Callaghan says no, but there are other publications that said yes, e.g. observation in Figure 1 of *Kinnersley and Pawson* [1996], and the modeling result of *McCormack* [2003].

Soukharev and Hood [2001] confirmed the conclusion of *Salby and Callaghan* [2000] using a composite analysis of the band-pass filtered 10 to 70hPa 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 line all start at 10hPa 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 40-50hPa levels. *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 period is -0.46 over the 17 westerly phases during the 1956-1996 period studied by Salby and Callaghan, 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 towards the end of his record in the 21th century, the relationship discovered by Salby and Callaghan appears to fail. It would be interesting to examine a longer data record further into the 21th century, when the stratosphere is not known to be contaminated by a major volcanic eruption. The eruption of Pinatuo in 1991 was cited as a possible reason for some of the problems with the correlation of Salby and Callaghan in the early 1990s.

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 phase 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 2005, since volcanic aerosols do not stay in the stratosphere for more than 5 years, most likely not longer than 3 years.

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 usefull. The use of CWT, which can determine the local period of an oscillation, gives a more objective method that is not sensitive to the location of the zero-wind line.

In this work, we shall reexamine the possibility of a decadal solar-cycle modulation of the period of the QBO using this objective method and the longest record available. It is the same in situ dataset 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 2005. Figure 1 shows the FUB zonal wind and also that from ERA-40 used for comparison. During the period of overlap, the winds from the two datasets are very close to each other. However, in 2001-2002, a noticeable difference on the zero crossing of the zonal wind exists, which may affect the period of the westerlies deduced using a subjective method. Also in 1992-1993, the monthly averaged zonal wind is close to zero but slightly below. The zonal wind may cross the zero line with a different time averaging. Wavelet transform, on the other hand, is more robust.

2. Review on Continuous Wavelets

We recall here only the main ideas underlying the wavelet theory and we refer to *Mallat* [1998] for a complete description. Any temporal signal, which can be seen as a one dimensional mathematical function, can be represented by a sum of fundamental functions called basis functions. The most famous example, the Fourier series,

$$s(t) = \sum_{k=-\infty}^{+\infty} c_k e^{ikt} \tag{1}$$

is valid for any 2π-periodic function sufficiently smooth. Each basis function, e^{ikt} is indexed by a parameter k which is related to a frequency. In (1), $s(t)$ is written as a superposition of harmonic modes with frequencies k. The coefficients c_n are given by the integral

$$c_k = \frac{1}{2\pi} \int_0^{2\pi} s(t) e^{-ikt} dt \tag{2}$$

Each coefficient c_k can be viewed as the average harmonic content of $s(t)$ at frequency k. Thus the Fourier decomposition gives a frequency representation of any signal. The computation of c_k is called the decomposition of s and the series on the right hand side of (1) is called the reconstruction of s.

Although this decomposition leads to good results in many cases, some disadvantages are inherent to the method. One of them is the fact that all the information concerning the local time behavior of the signal is lost in the Fourier decomposition. For instance, a discontinuity or a localized high variation of the frequency will not be described by the Fourier representation in any intuitive or useful manner. The underlying reason lies in the nature of complex exponential functions used as basis functions. They are global functions that span the entire data record and differ only with respect to frequency.

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:

$$WT_b^a = \int dt\, s(t)\, \psi_{a,b}(t), \tag{3}$$

where $\psi_{a,b}(t)$ plays the same part as the exponential functions in the Fourier transform. A possibility is to construct the set $\{\psi_{a,b}(t)\}_{a \in R^*, b \in \mathbb{R}}$ from a function $g(x)$ by translating and modulating it:

$$\psi_{a,b}(t) = g(t-b)\, e^{iat}, \tag{4}$$

where $g(t)$ is a window function. In spite of the improvement brought by this "pseudo-spectral" representation, this transformation is still not adapted to describing accurately functions which exhibit high local variations. To overcome this disadvantage (a fixed size window function), analyzing functions with time support widths adapted to their frequency are needed.

The idea is to apply dilations on top of translations previously introduced. Starting with a function ψ well localized in time and frequency spaces, a family of analyzing functions can be constructed:

$$\psi_{a,b}(t) = |a|^{-1/2}\,\psi\left(\frac{t-b}{a}\right). \tag{5}$$

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:

$$\int d\xi\,\frac{|\hat{\psi}|^2}{|\xi|} = K < \infty. \tag{6}$$

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 (3) give a time-scale representation of the initial signal allowing the detection of transcient components or singularities.

The results presented in this paper have been obtained using the tenth derivative of the Gaussian as a wavelet mother. 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.

3. Results and Discussion

3.1. QBO-period variation

Figure 2 shows the local period of the QBO oscillation as determined by applying the CWT to the FUB data at 50 hPa for the period 1953-2005. This radiosonde dataset of near equatorial zonal wind consists of observations at Canton Island (January 1953 - August 1967) , Gan, Maldives (September 1967 - 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 this figure shows the amplitude of the wavelet coefficients, with darker color indicating higher amplitudes. The maximum amplitude of these wavelet coefficients is marked in a dashed line in Figure 2. This marks the dominant period of the equatorial 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.

Figure 2 shows that, consistent with Salby and Callaghan, 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, however, the anti-correlation 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 with the finding of Hamilton. Going forward in time, the correlation is the reverse of that of Salby and Callaghan. 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. Prior to 1957, 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 anti-correlation 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 (-0.05) for the long record of 1953-2005. It is intriguing to note the alternate correlation and anti-correlation 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.

3.2. Comparison with the subjective method

Figure 3 shows in the upper panel a comparison of the period as determined objectively using CWT and the subjectively determined period by measuring the length between successive zero crossing of the zonal wind. It turns out 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. Our method turns out to be consistent with the average of these two definitions, provided that monthly averages are used in the subjective method. The easterly plus westerly period appears to have a few more oscillations in 1980-1990. By comparing with the objectively determined period, one can perhaps attribute it to an artifact and not to volcanoes or the solar cycle.

On the lower panel of Figure 3, 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 track quite closely that of the full QBO period as determined by the CWT. Therefore our conclusion that there is no correlation of the QBO period with the solar cycle also applies to the westerly phase separately. The correlation coefficient of the westerly-phase period variation with the sunspot time series for the full period of 1953-2005 is -0.10.

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

3.3. Behavior at different pressure levels

To answer the question of whether the QBO period changes with height, Figure 4 shows the QBO period obtained the same way as in Figure 2 using the FUB data for various pressure levels from 70 hPa to 15 hPa. It shows the same prominent decadal variation at all levels and that the difference are small with respect to height. Minor exceptions exist at the higher levels and at 70hPa prior to 1958. These calculations were also repeated with the ERA-40 data, and the results were similar to those obtained using the FUB data for the period of overlap.

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 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. Above 30 hPa, there is no stalling of the easterlies. The slower descent of the easterlies then gives a longer easterly period. Below the level of stalling of the easterlies (near 30 hPa) however, there is no easterlies. Instead the westerlies at those levels persist without being replaced by the descending easterlies. 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.

4. Conclusion

The longer equatorial zonal wind dataset from Free University of Berlin (1953-2005) spans almost six solar cycles. We have found that during three of the cycles the period of the QBO is anti-correlated with the solar cycle, while in the remaining almost three cycles, there is correlation with the solar-cycle flux. Consequently over the five and a half solar cycles the correlation coefficient is zero. The period previously considered by *Salby and Callaghan* [2000] contains three anti-correlated periods with one "straddling" period in 1992, which could be discounted as due to Pinatubo. With our longer record extending into 2005, when there has not been a major volcanic eruption since 1991, it becomes more difficult to attribute the "anomalous" behavior to volcanic aerosols. Our result strengthens that of *Hamilton* [2002] by using a longer data record, a more objective method of determining local period, and by showing that our conclusion is the same for all levels in the lower stratosphere. Our result however does not rule out the effect of solar cycle on the QBO period. It is rather intriguing to find that the variation of the QBO period is not random, but follows closely the variation of the solar cycle. It is only that the correlation completely reverses itself after three solar cycles. The possibility exists that it is the period of 1960s, 1970s, 1980s and 1990s that is anomalous, with three major volcanic eruptions (Agung in 1963, El Chichon in 1982 and Pinatubo in 1991), and instead the QBO period should actually be shorter at solar minimum and longer at solar maximum in the absence of volcanic aerosols. *Angel* [1986] argued that the prolongation of the westerly phase after the Agung eruption in 1963 was probably due to the aerosol heating; the temperature increase was also seen at 50 and 30 hPa at Balboa station. He also suggested that the higher altitude reached by the El Chichon aerosol in 1982 produced a "shielding" effect at 50 hPa, which might have prevented the aerosol heating at that altitude in 1982. The mechanism of solar cycle influence of the equatorial QBO remains yet to be discovered.

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Figure captions:

Figure 1: The monthly mean zonal wind at 50 hPa as a function of years. The dashed line shows the radiosonde data at near equatorial stations compiled by the Stratospheric Group at Free University of Berlin. The solid line shows the mean zonal wind in the ERA-40 dataset maintained at European Center for Medium Range Weather Forecasting.

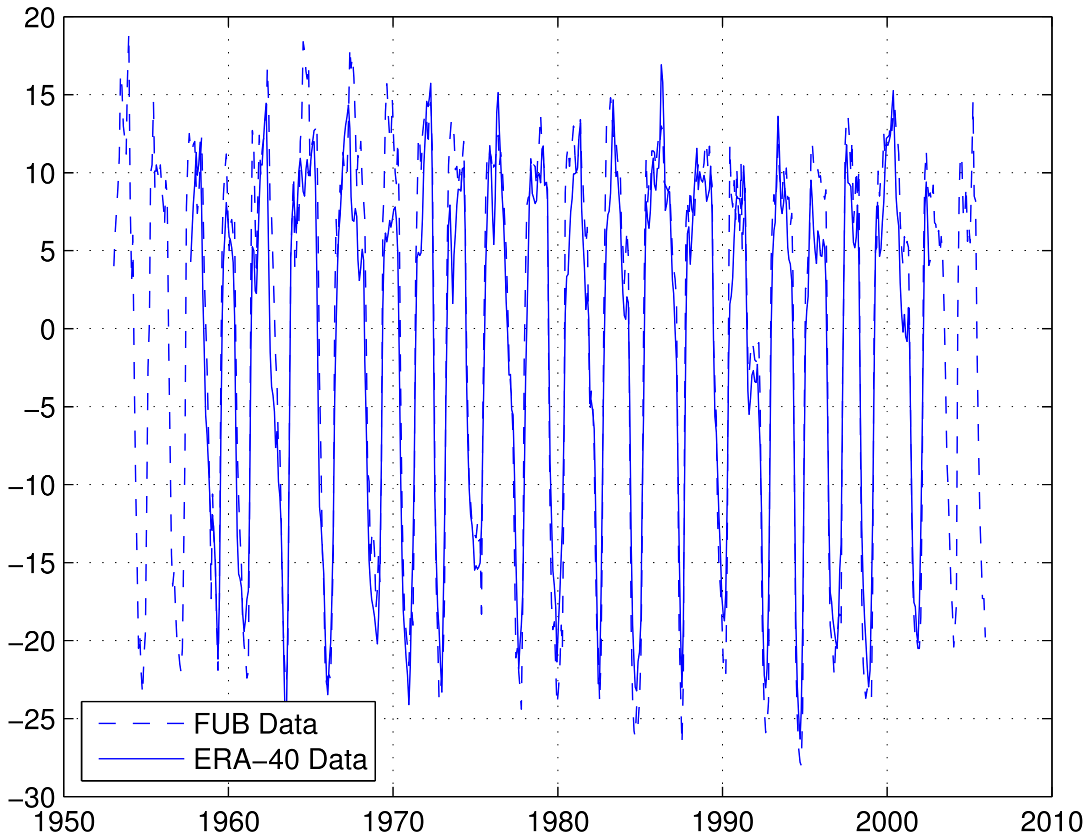
Figure 2: Local period in months of the 50 hPa FUB wind as determined by the CWT. The darker region denotes location of higher amplitude of the zonal wind. The dashed line traces the location of the maximum amplitude. Superimposed, in solid line, is the sunspot number (monthly averaged), which is a proxy for the solar cycle radiative flux variability.

Figure 3: Upper panel: 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)

Lower panel: The westerly phase duration (in dashed line) and the easterly phase duration (in dotted line).

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

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.



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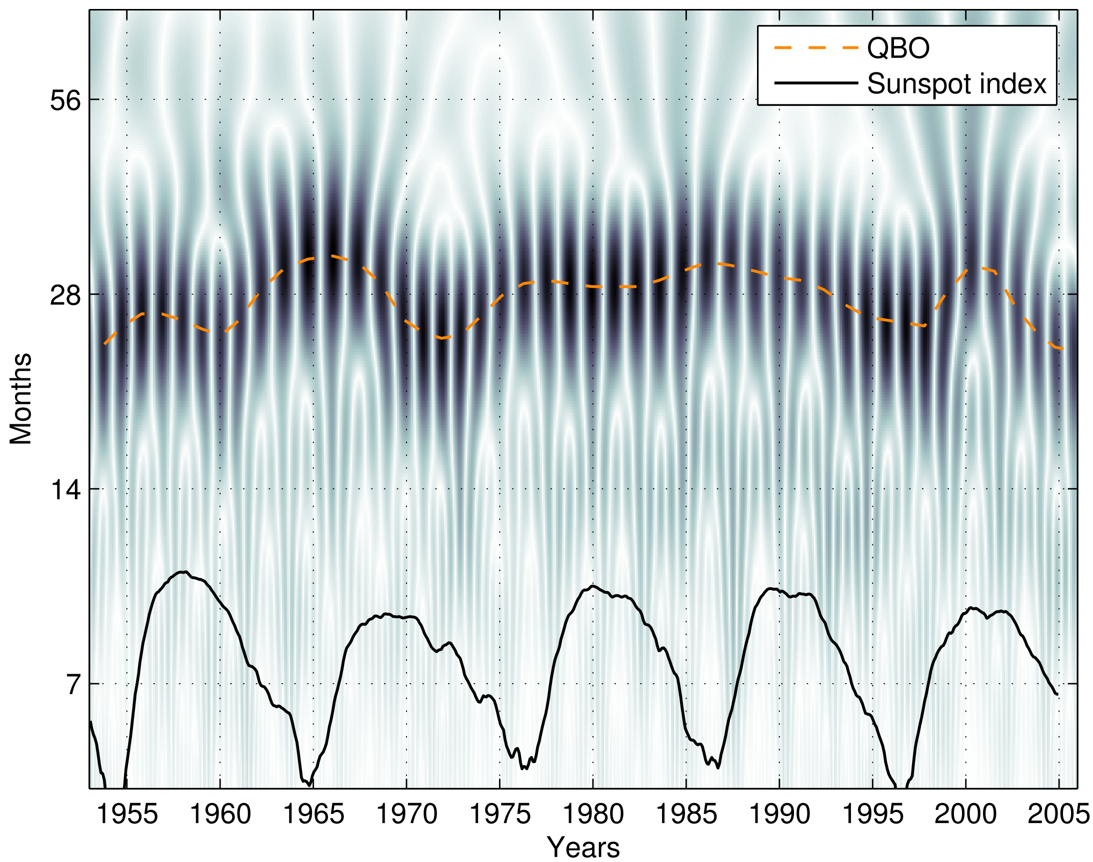

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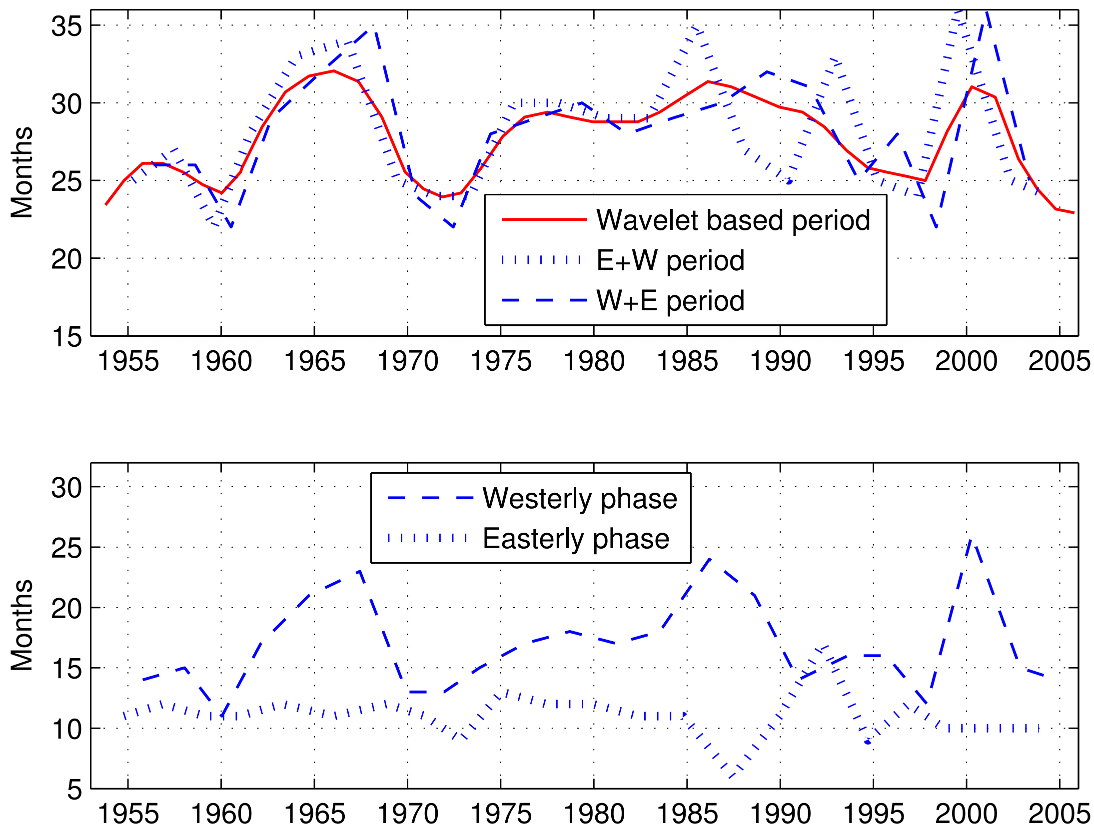

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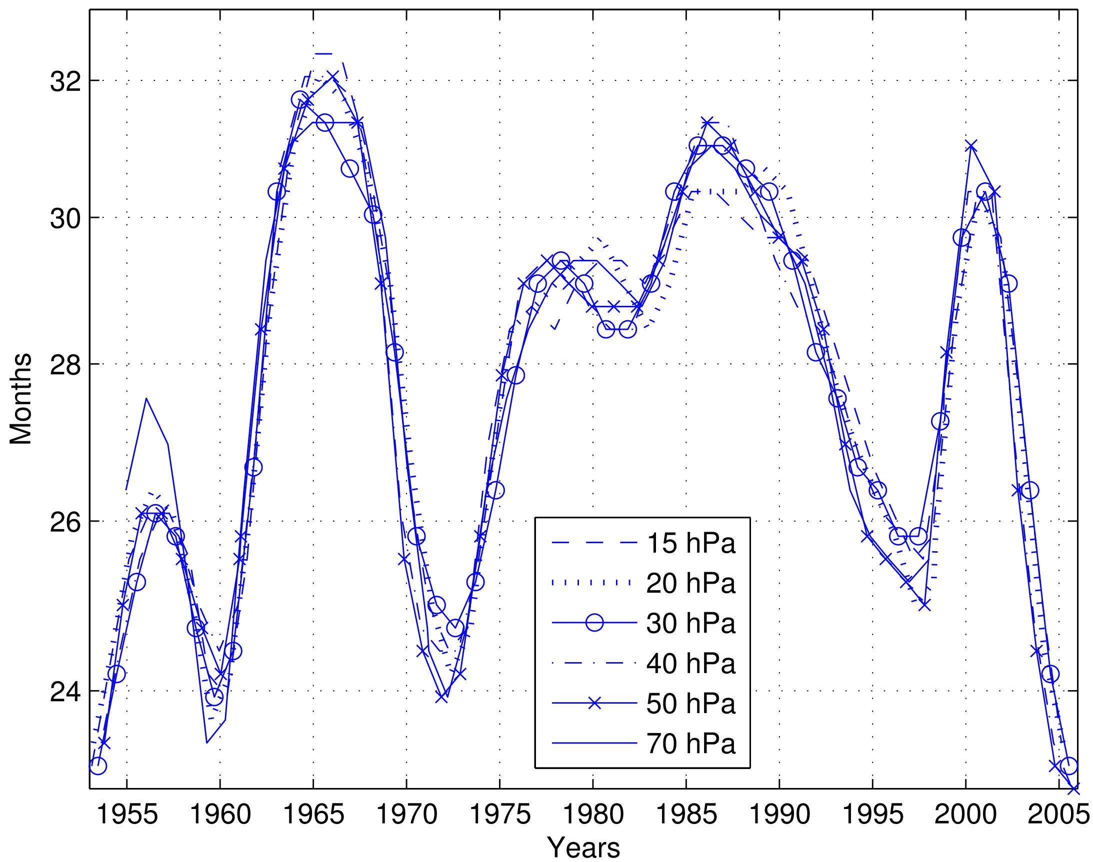

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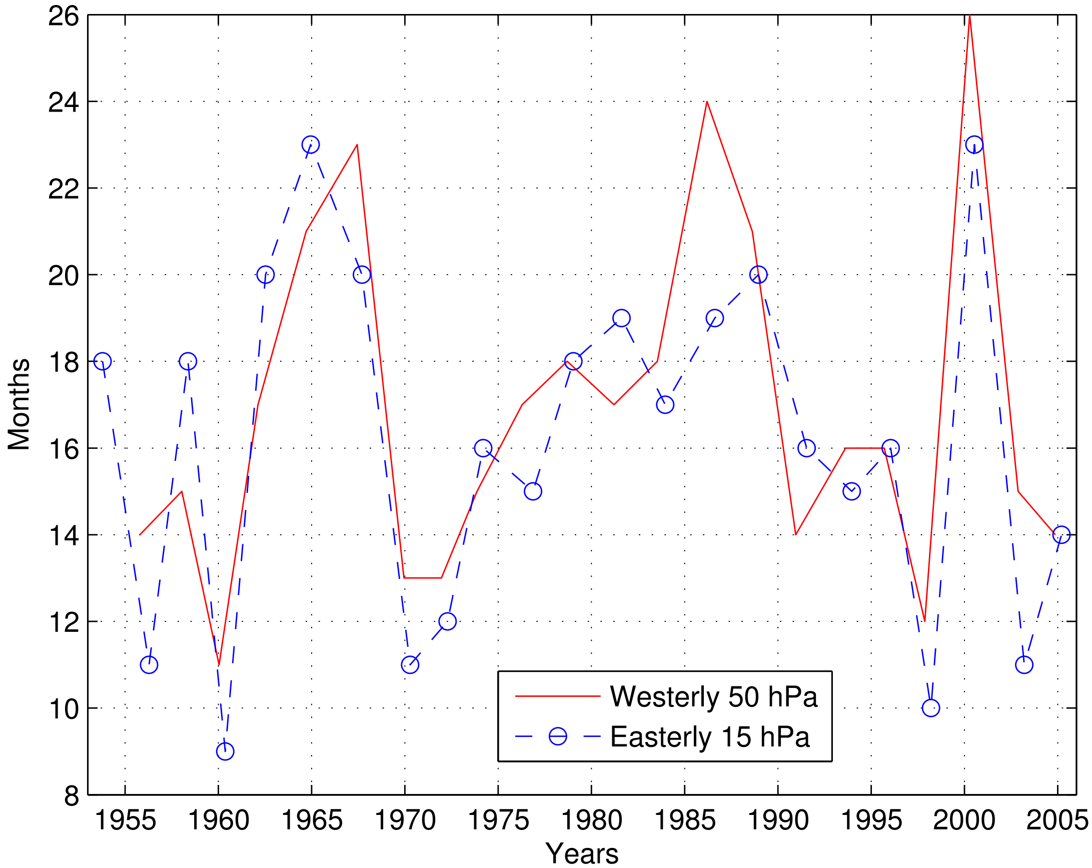

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