

## Modeling the Observed Solar Cycle Variations of the Quasi-biennial Oscillation (QBO): Amplification by Wave Forcing

### Popular Summary

In several papers, the solar cycle (SC) effect in the lower atmosphere has been linked observationally to the Quasi-biennial Oscillation (QBO) of the zonal circulation, which is generated primarily by small-scale gravity waves (GW). Salby and Callaghan (2000) in particular analyzed the QBO, covering more than 40 years, and discovered that it contains a large SC signature at 20 km. With our Numerical Spectral Model (NSM), we conducted a 3D study to describe the QBO under the influence of the SC, and some results have been published (Mayr et al., GRL, 2005, 2006). For a SC period of 10 years, the relative amplitude of radiative forcing is taken to vary exponentially with height, i.e., 0.2% at the surface, 2% at 50 km, 20% at 100 km and above. Applying spectral analysis to filter out and identify the SC signature, the model generates a relatively large modulation of the QBO, which reproduces the observations qualitatively. Our numerical results demonstrate that the modulation of the QBO, with constant phase relative to the SC, persist at least for 60 years. The same model run generates in the seasonal variations a hemispherically symmetric Equatorial Annual Oscillation (EAO, with 12-month period), which is confined to low latitudes like the QBO and is also modulated by the SC. Although the amplitude of the EAO is relatively small, its SC modulation is large, and it is in phase with that of the QBO. The SC modulated EAO is evidently the pathway and pacemaker for the solar influence on the QBO. To shed light on the dynamical processes involved, we present model results that show how the seasonal cycle induces the SC modulations of the EAO and QBO. Our analysis further demonstrates that the SC modulations of the QBO and EAO are amplified by the GW interaction with the flow. The GW momentum source clearly shows a SC modulation that is in phase with the corresponding modulations of the QBO and EAO. By tapping the momentum from the upward propagating GWs, the QBO and EAO apparently serve as conduits to amplify and transfer to lower altitudes the larger SC variations in the UV absorbed in the mesosphere. Our model also produces in the temperature variations of the QBO and EAO measurable SC modulations at polar latitudes near the tropopause, and such signatures have been reported in the literature. Contrary to conventional interpretation, however, we suggest that the effects are generated at least in part by the meridional circulation, and planetary waves presumably, which redistribute the energy from the equatorial region where wave forcing is very efficient and thereby amplifies the SC influence.

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## **Modeling the Observed Solar Cycle Variations of the Quasi-biennial Oscillation (QBO): Amplification by Wave Forcing**

In several papers, the solar cycle (SC) effect in the lower atmosphere has been linked observationally to the Quasi-biennial Oscillation (QBO) of the zonal circulation, which is generated primarily by small-scale gravity waves (GW). Salby and Callaghan (2000) in particular analyzed the QBO, covering more than 40 years, and discovered that it contains a large SC signature at 20 km. With our Numerical Spectral Model (NSM), we conducted a 3D study to describe the QBO under the influence of the SC, and some results have been published (Mayr et al., GRL, 2005, 2006). For a SC period of 10 years, the relative amplitude of radiative forcing is taken to vary exponentially with height, i.e., 0.2% at the surface, 2% at 50 km, 20% at 100 km and above. Applying spectral analysis to filter out and identify the SC signature, the model generates a relatively large modulation of the QBO, which reproduces the observations qualitatively. Our numerical results demonstrate that the modulation of the QBO, with constant phase relative to the SC, persist at least for 60 years. The same model run generates in the seasonal variations a hemispherically symmetric Equatorial Annual Oscillation (EAO, with 12-month period), which is confined to low latitudes like the QBO and is also modulated by the SC. Although the amplitude of the EAO is relatively small, its SC modulation is large, and it is in phase with that of the QBO. The SC modulated EAO is evidently the pathway and pacemaker for the solar influence on the QBO. To shed light on the dynamical processes involved, we present model results that show how the seasonal cycle induces the SC modulations of the EAO and QBO. Our analysis further demonstrates that the SC modulations of the QBO and EAO are amplified by the GW interaction with the flow. The GW momentum source clearly shows a SC modulation that is in phase with the corresponding modulations of the QBO and EAO. By tapping the momentum from the upward propagating GWs, the QBO and EAO apparently serve as conduits to amplify and transfer to lower altitudes the larger SC variations in the UV absorbed in the mesosphere. Our model also produces in the temperature variations of the QBO and EAO measurable SC modulations at polar latitudes near the tropopause, and such signatures have been reported in the literature. Contrary to conventional interpretation, however, we suggest that the effects are generated at least in part by the meridional circulation, and planetary waves presumably, which redistribute the energy from the equatorial region where wave forcing is very efficient and thereby amplifies the SC influence.

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## 1. Introduction

Solar cycle (SC) signatures in the lower atmosphere have been linked observationally to the Quasi-biennial Oscillation (QBO), which dominates the zonal circulation of the lower stratosphere at equatorial latitudes. Labitzke (1982, 1987) and Labitzke and van Loon (1988, 1992) discovered that the temperatures at northern polar latitudes in winter are positively and negatively correlated with the SC when the QBO is in its negative and positive phase respectively. They observed opposite correlations at mid-latitudes. In the stratosphere at northern latitudes, Dunkerton and Baldwin (1992) and Baldwin and Dunkerton (1998) found evidence of a quasi-decadal oscillation correlated with the QBO and SC.

The QBO itself also contains a relatively large SC signature. This was discovered by Salby and Callaghan (2000), who analyzed the 40-year record of measured QBO zonal winds at about 20 km altitude. In their paper, the power spectrum shows a sharp peak at 0.41 cycles per year (cpy), representing a QBO period of about 29 months. Smaller neighboring peaks in the spectrum at 0.5 and 0.59 cpy reveal difference frequencies, which represent the SC modulations of the QBO with a period of 11 years and its second harmonic of 5.5 years, respectively. Salby and Callaghan synthesized the spectral features around the QBO, which shows that, correlated with the SC, the wind power varies at 20 km from about 150 to 400 m<sup>2</sup>/s<sup>2</sup> or from 12 to 20 m/s. Analyzing 50 years of wind measurements, Hamilton (2002) confirmed the quasi-decadal modulation of the QBO reported by Salby and Callaghan (2000) but concluded that the connection to the SC is not as clear in the longer data record.

In a study with the Numerical Spectral Model (NSM), the observed SC modulation of the QBO (Salby and Callaghan, 2000) has been qualitatively reproduced (Mayr et al., 2005, 2006). With the present paper, we review the salient features of the model and discuss numerical results that provide understanding of the processes involved. In Section 2, the dynamical properties of the QBO are discussed. In Section 3, the 3D version of the NSM is briefly described. In Section 4, our model results are presented for the SC modulation of the QBO. In Section 5, numerical results are presented that illuminate the dynamical processes in which the SC effect is generated through the seasonal cycle and with wave forcing. In Section 6, we summarize our findings and present the conclusions.

## 2. QBO and Wave-Driven Equatorial Oscillations

The QBO, with periods between 22 and 34 months and reviewed by Baldwin et al. (2001), is confined to low latitudes where it dominates the zonal circulation of the lower stratosphere. In the equatorial circulation of the upper stratosphere and mesosphere, the Semi-annual Oscillation (SAO) dominates (Hirota, 1980). It was demonstrated by Lindzen and Holton (1968), Holton and Lindzen (1972), and others (e.g., Plumb, 1977; Dunkerton, 1985) for the QBO, and by Dunkerton (1979) and Hamilton (1986) for the SAO, that these equatorial oscillations are driven by the momentum deposition from upward propagating waves. Eastward propagating Kelvin waves and westward propagating Rossby gravity waves were originally invoked to drive the oscillations. Later modeling studies with observed planetary waves, however, have led to the conclusion that small-scale gravity waves (GW) appear to be more important (e.g., Hitchman and Leovy, 1988). With a general circulation model (GCM) that resolves the

planetary waves, Hamilton et al. (1995) showed that the stratospheric QBO was an order of magnitude smaller than observed, thus providing further circumstantial evidence for the importance of GWs. Except for a few attempts at simulating the QBO with resolved GWs (e.g., Takahashi, 1999), these waves need to be parameterized for global-scale models (e.g., Giorgetta et al., 2002). Applying Hines' GW parameterization, we were among the first to reproduce with our 2D model the QBO and SAO extending from the stratosphere into the upper mesosphere (e.g., Mengel et al., 1995; Mayr et al., 1997). Although the GW source was taken to be latitude independent, the modeled QBO of the zonal circulation was confined to equatorial latitudes, as observed -- and Haynes (1998) provided an analytical explanation.

This latter property of the QBO is one of the factors that become important for the SC mechanism we discuss here. As Linzen and Holton (1968) emphasized, at the equator where the Coriolis force vanishes, the wave forcing is only balanced by viscous dissipation. The wave source is therefore extremely efficient in accelerating the zonal wind oscillations around the equator; while away from the equator, the meridional circulation comes into play to redistribute and dissipate the flow. In this context, the other important factor is the long time constant for eddy viscosity in the lower stratosphere; it is on the order of years and thus is favorable for generating the QBO and its long-term SC modulation.

Finally, an important property of the QBO is that its periodicity and amplitude are highly variable and susceptible to external influence. In the seminal theory for the QBO by Lindzen and Holton (1968), the seasonal cycle and resulting Semi-annual Oscillation (SAO) were invoked to seed the QBO. Holton and Lindzen (1972) later concluded that the seasonal cycle was not essential to generate the oscillation. This was confirmed with 2D computer experiments (Mayr et al., 1998), where QBO like oscillations were generated, (a) for perpetual equinox and (b) with the regular seasonal cycle of solar heating. The seasonal cycle lengthened the period of the QBO from 17 to 21 months and more than doubled its amplitude in the lower stratosphere. Influenced by the seasonal variations, the QBO thus could be affected also by the SC, whose signature then would be transferred to lower altitudes under the influence of wave-mean-flow interactions.

To explore this mechanism, Mayr et al. (2003b) carried out two computer experiments with the 2D version of the NSM. For both studies, the model was run with and without the SC, and the differences in the zonal winds were analyzed. In the first case, the QBO had a period of 30 months, which is exceptionally stable because it is synchronized by the seasonal cycle. The SC then modulated only the QBO amplitude, and the effect, though significant, was relatively small. In the second case, the QBO period of  $\sim 33$  months was variable and susceptible to the SC influence. The SC then affected not only the amplitude of the QBO but its phase and periodicity as well, which produced large differences in the zonal winds.

### **3. 3D Numerical Spectral Model (NSM)**

The NSM was introduced by Chan et al. (1994), and 2D as well as 3D applications were employed to describe the wave-driven equatorial oscillations (QBO and SAO), and the tides and planetary waves in the middle atmosphere (e.g., Mengel et al., 1995; Mayr et al., 1997, 2003; Mayr and Mengel, 2005). For the zonal mean ( $m = 0$ ), the NSM is driven by the absorption of EUV and UV radiation, with the heating rates taken from Strobel

(1978). A time-independent heat source in the upper troposphere reproduces qualitatively the observed zonal jets and temperature variations near the tropopause. The radiative loss is described in terms of Newtonian cooling, and we adopt for that the parameterization developed by Zhu (1989). The rate coefficient from this parameterization is not well determined at lower altitudes but continues to decrease towards the ground. To assure that the cooling rate is not too low, we were guided by Dunkerton (1997) and keep it constant below 20 km. For the migrating solar tides, the heating rates in the middle atmosphere and troposphere are taken from Forbes and Garrett (1978).

An integral part of the NSM is that it incorporates the Doppler Spread Parameterization (DSP) for GWs developed by Hines (1997a, b). This parameterization deals with a spectrum of waves that interact with each other to produce Doppler spreading, which affects their interactions with the flow. In the present version of the NSM, a latitude dependent tropospheric GW source is adopted that peaks at the equator to account for the enhanced wave activity associated with convection in the tropics. The source is taken to be isotropic and time independent.

In the NSM, the planetary waves are generated solely by instabilities. Our model does not account explicitly for the eastward propagating Kelvin waves and westward propagating Rossby gravity waves that are produced by convection at low latitudes. As discussed earlier, these waves could generate the QBO in principle (Lindzen and Holton, 1968). But GCM simulations that resolve the waves fail to generate the QBO (e.g., Hamilto et al., 1995), while models with GWs do reproduce the oscillation.

With the upper boundary at 130 km, a small vertical integration step of about 0.5 km is employed to resolve the GW interactions with the flow. The model is truncated at the zonal and meridional wave numbers  $m = 4$  and  $l = 12$ , respectively.

We assume for simplicity that the period of the SC is 10 years, constant throughout the entire model run, and the adopted height profile of solar heating is similar to that employed earlier (Mayr et al., 2003). The amplitude of relative variation of solar radiation for the zonal mean ( $m = 0$ ) heat source is taken to be 0.2% at the surface, 2% at 50 km, and 20% at 100 km and above. With the initial conditions set to zero for all the state variables, including winds and temperature perturbations, the 3D version of the NSM was run with and without the SC to cover several decades.

#### **4. Solar Cycle Variations of Equatorial Zonal Winds**

As stated, the basic results from our modeling study for the SC modulation of the QBO have been published (Mayr et al., 2005, 2006). In this paper, we provide insight into the processes that generate the SC modulations, and for this purpose the model was run again up to 60 years to record the GW momentum source (MS). The numerical results for the MS will be discussed later, and for completeness we present here the modeled SC modulations of the zonal winds near the equator.

##### **4.1. SC Modulated QBO**

In Figure 1a, we show the power spectrum for the zonal winds at 4° latitude (Gaussian point) obtained from the computer run with SC covering the period from 10 to 60 years (ignoring the first 10 years to allow for spin up). The hemispherically symmetric component is shown that dominates near the equator. Applying Fourier analysis, the amplitudes for the discrete harmonics,  $h$ , are recorded as functions of altitude, and contours are drawn to produce the figure. For the time span of 50 years, the

QBO is well defined at harmonic  $h = 27$ , which represents a period of  $50/16$  (years) = 22.22 months. The spectrum also shows separate individual features, and the ones at  $h = 22$  and  $32$  are of interest for the present study. Displaced from the dominant QBO at  $h = 27$  by 5 wave numbers, the side lobes are the signatures of the 10-year SC modulation. These spectral features are produced by non-linear interactions involving the QBO and 10-year SC forcing. With abbreviated complex notation, the product between QBO,  $A \exp[i(\omega_a t)]$ , and SC,  $B \exp[i(\omega_b t)]$ , generates the sum and difference of the frequencies involved, i.e.,  $C_1 \exp[i(\omega_a + \omega_b)t]$  and  $C_2 \exp[i(\omega_a - \omega_b)t]$ .

Corresponding to the spectrum in Figure 1a, we present in Figure 1b the synthesis of the QBO with the 10-year side lobes that describe the SC signature. (Although shown only for 15 years, the pattern represents the 50-year average of the QBO/SC modulation.) From Figure 1b it is apparent that the magnitude of the computed SC modulation is relatively large, causing the QBO amplitude to increase from about 10 to 17 m/s at 30 km. For comparison, we present with dashed line the phase of the imposed SC heating. The peak of the QBO amplitude occurs close to the SC maximum. The results shown here are identical to those presented in Mayr et al. (2006). In that paper, we recorded also the solution for the model run from 10 to 40 years (30-year time span) to demonstrate the persistence of the SC modulation. Without SC for comparison, the computed 10-year modulations of the QBO are comparatively small and irregular, which reflects the lack of systematic solar forcing.

#### 4.2. SC Modulated Equatorial Annual Oscillation (EAO)

Our numerical results show that the modeled QBO contains a pronounced and persistent SC signature -- and the question is what causes the effect. Observational evidence indicates (e.g., Dunkerton and Delisi, 1997) that the seasonal cycle influences the QBO, and our modeling studies support that (e.g., Mayr et al., 1998). In search of a SC signature, we found that a hemispherically symmetric 12-month annual oscillation (AO) is involved, not the symmetric semi-annual oscillation, and this was shown in Mayr et al. (2005) for the time span from 10 to 40 years. Like the QBO, this symmetric AO is confined to latitudes around the equator and is therefore referred to as Equatorial Annual Oscillation (EAO).

With the format of Figure 1, we present in Figure 2 the results for the computed EAO near the equator obtained from the model run up to 60 years covering a 50-year time span. In the power spectrum (a), the 12-month AO occurs at the harmonic  $h = 50$ , and the side lobes for the 10-year SC occur at  $h = 45$  and  $55$  (i.e.,  $50 \pm 5$ ). The synthesized zonal winds (b) for the EAO reveal a pronounced SC modulation, and the amplitude maximum occurs close to the peak of the solar forcing whose phase is shown with dashed line. When the synthetic SC modulations of the EAO are examined for time spans from 30 to 50 years, the maximum amplitudes between 30 and 50 km are found to decrease from almost 6 to 3.5 m/s -- likely due to the interference from a 15-year oscillation, generated internally, which is discussed in Mayr et al. (2005). The maximum amplitude then increases again to reach values around 5.5 m/s for the time spans of 60 and 70 years. Irrespective of the variable amplitude maximum, we find that the phase relationship relative to the SC remains constant due to the imposed systematic solar forcing.

For the present modeling study, the EAO is important because its SC modulation is in phase with that of the QBO as is evident from Figures 1b and 2b. Acting as pacemaker, the EAO is evidently the pathway for transmitting the SC influence to the QBO.

As emphasized in Mayr et al. (2005), and illuminated in Figure 1 of that paper, the EAO represent an anomalous mode of the AO in that it is symmetric, in contrast to the dominant AO that is hemispherically anti-symmetric. Although the anti-symmetric AO is much larger, even at  $4^\circ$  latitude close to the equator, the SC modulated symmetric mode extends to lower altitudes. Driven by wave mean flow interactions that are very efficient in amplifying oscillations around the equator, the EAO slowly propagates down like the QBO.

## **5. Mechanisms for Generating Solar Cycle Modulations**

The above-discussed results indicate that the SC signature is transferred to the QBO in the form of an anomalous symmetric annual oscillation, the EAO, which acts as pacemaker, and we can show how it is generated in the model. The SC modulations of the QBO and EAO appear to be amplified by tapping the momentum flux from the upward propagating GWs, and we can demonstrate that with our model results.

### **5.1. Solar Cycle Forcing**

To shed light on the process that generates the EAO in the model, we present with Figure 3a the spectrum for the anti-symmetric component of the zonal winds at  $11^\circ$  latitude. (This component vanishes at the equator.) Two regimes are shown in the spectrum. One covers the harmonics  $0 < h < 7$  to reveal the long-term variations including the 10-year periodicity at  $h = 5$  that describes the SC signature. The other one covers only the harmonics around  $h = 50$  to describe the dominant anti-symmetric AO with a period of 12 months. The spectral feature describing the SC is sharp and it peaks at altitudes around 65 km. In Figure 3b, we present then for 60 km the latitude dependence of the 10-year anti-symmetric SC signature that is generated in the model. This SC component extends to high latitudes, but it is largest close to  $10^\circ$  near the equator. Although the amplitude in Figure 3b is small, the dominant AO in Figure 3b at  $h = 50$  is relatively large, so that the product between the two anti-symmetric oscillations could generate the small but symmetric SC modulation of the EAO shown in Figure 2.

### **5.2. Gravity Wave Momentum Source (MS)**

Unlike the basic state variables of temperature and winds, which are recorded for each zonal wave number as part of the solution, the GW momentum source (MS) in the NSM is computed in physical space like the non-linearities. In the format used to record the MS, the generated model output covers all wave numbers ( $m = 0$  to 4), and thus it is much larger than that for the  $m = 0$  temperatures and winds we have discussed. To reduce the model output, the MS has therefore been recorded with 5 km altitude steps instead of the 0.5 km resolution for the NSM. Although this limitation blemishes the displayed MS, it does not affect the conclusions.

Adhering to the format of contour plots (Figures 1 and 2), with spectra and synthesized SC variations, we present in Figure 4 the corresponding MS for the SC modulation of the QBO. Since the MS varies exponentially with height, it is normalized such that the altitude dependence is eliminated -- which preserves the relative SC variations of interest.

In Figure 4a, as expected, the amplitude maximum for the MS occurs at  $h = 27$ , corresponding to the period of 22.22 months for the zonal winds in Figure 1a. This sharp spectral line dominates at altitudes between 10 and 50 km, which is commensurate with



the GW forcing of the stratospheric QBO. Weaker spectral lines are also apparent at  $h = 22$  and  $32$  that describe the SC modulation with a period of 10 years.

A synthesis of the MS for the harmonics  $h = 27, 22$  and  $32$  is presented in Figure 4b to show the SC modulation of the wave forcing (with contour interval of 2, and normalized maximum amplitude of 10). From this it is apparent that the MS varies in the lower stratosphere by as much as a factor of 2, and it varies in phase with the SC. The MS thus contributes to the SC modulation of the QBO and thereby amplifies effectively the influence of the solar variability in the lower stratosphere.

Analogous to Figure 4, we present in Figure 5 the normalized MS for the Equatorial Annual Oscillation (EAO), which is involved in generating the zonal wind oscillations (Figure 2) that in turn induce the SC modulation of the QBO. As is the case for the QBO, the spectrum in Figure 5a is ragged due to the 5-km resolution of the recorded MS. The spectral features displayed nevertheless reveal the salient features that describe the SC modulation of the EAO. At  $h = 50$ , the 12-month oscillation is apparent, and the side lobes at  $h = 45$ , and  $55$  in particular, describe the 10-year SC variation of the annual oscillation. As in Figures 1, 2 and 4, the hemispherically symmetric component is shown.

In Figure 5b, the synthesis is presented for the harmonics  $h = 50, 45$  and  $55$  to reveal the SC variations of the EAO. Commensurate with the large amplitude variation of the EAO in Figure 2, the related MS also varies considerably. With respect to the SC, the phase relationships of zonal winds and MS are also essentially the same.

## 6. Summary and Conclusions

Based on the above-described mechanisms, it is apparent that the SC influence on the stratospheric QBO in our model involves four interlocking stages.

(1) The variable but systematic solar forcing produces a 10-year SC component in the mesosphere (60 km), shown in Figure 3b, which is hemispherically anti-symmetric (with opposite phase in the two hemispheres).

(2) This anti-symmetric SC component interacts with the dominant anti-symmetric AO (shown in Figure 3a at  $h = 50$ ) to produce the symmetric SC modulated EAO in Figure 2. The EAO is then amplified by wave interaction (Figure 5b) and propagates down to lower altitudes like the QBO.

(3) The modulated EAO acts as pacemaker for the SC modulation of the QBO as seen from Figure 1b compared with Figure 2b.

(4) The SC modulated QBO is amplified by the GWs (Figure 4b). The QBO thus becomes the conduit that amplifies and transfers to the lower stratosphere the influence from the larger SC variations in the UV absorbed in the mesosphere.

The processes involved in generating the SC modulation of the QBO in our model have in common that they characterize the dynamical properties of the equatorial region in the middle atmosphere. We recall what these properties are:

(a) With the Coriolis force vanishing at the equator, absent dissipation by the meridional circulation, the wave forcing is very efficient because it is only dissipated by viscosity. The QBO, and equatorial oscillations in general, therefore tend to peak at the equator.

(b) Related to that property, the eddy viscosity (generated by wave dissipation) decreases at lower altitudes to produce time constants on the order of years, which



partially determines the QBO period and favors the generation of SC-related long-term variations.

(c) While QBO-like oscillations can be generated in principal without time dependent forcing, numerical experiments show that external sources affect significantly the amplitude and period of the QBO. This property we believe makes the QBO pliable and amenable to be guided by the SC modulated EAO that acts as pacemaker.

In the present paper, we concentrated on the processes that generate the equatorial oscillations of the zonal circulation. As shown in Mayr et al. (2005, 2006), the QBO and EAO related temperature variations in our model extend into the Polar Regions to produce measurable SC effects near the tropopause. We do not yet fully understand how the signatures are transferred from the equatorial region towards higher latitudes, but the meridional circulation is likely involved since the effects also appear in the 2D model.

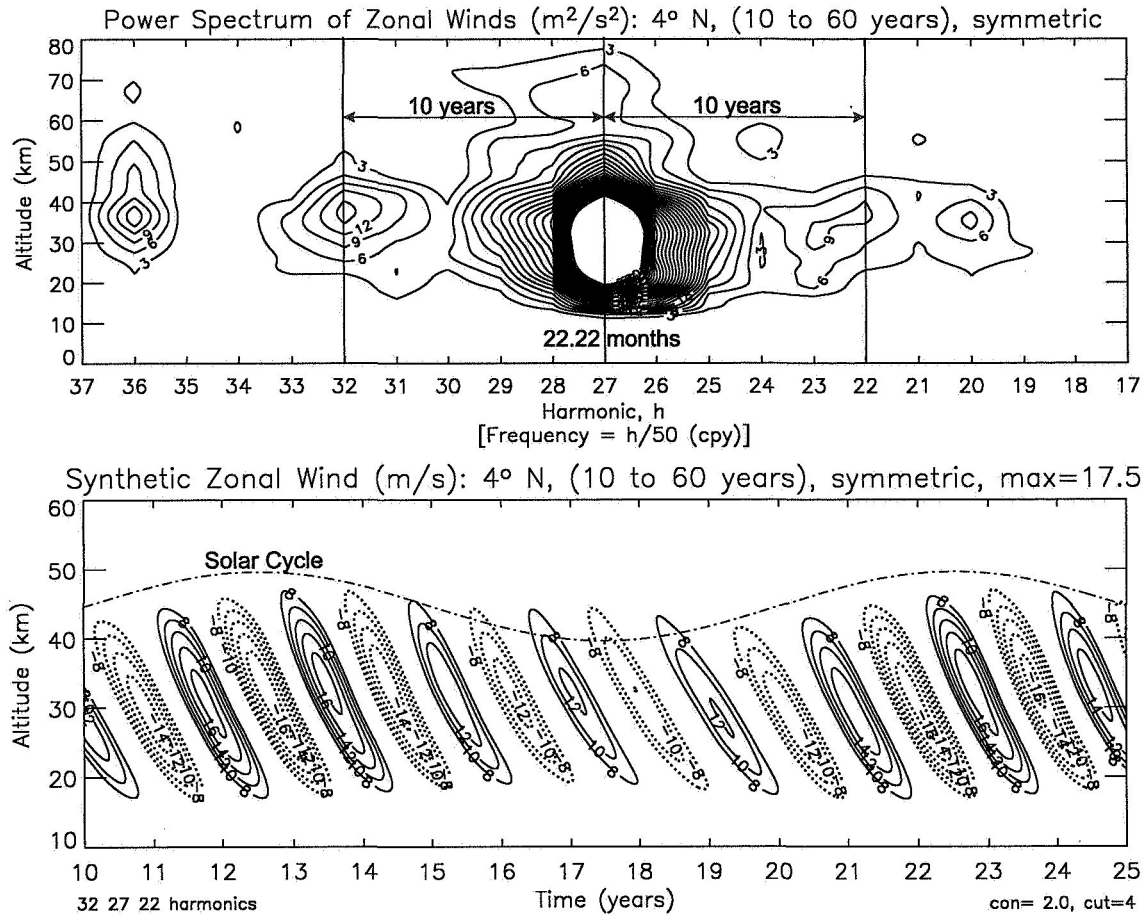
To our knowledge, a SC modulated hemispherically symmetric annual oscillation, labeled Equatorial Annual Oscillation (EAO) for the zonal winds near the equator, has not been reported in the literature. Mayr et al. (2005) suggested that this oscillation may be involved in generating the so-called Arctic Oscillation, which appears to propagate down from the stratosphere and is found to be sensitive to solar cycle influence (Kodera, 1995; Thompson and Wallace, 1998; Baldwin and Dunkerton, 1999; Ruzmaikin and Feynman, 2002). Contrary to conventional interpretation, we believe that this hemispherically symmetric oscillation originates at low latitudes around the equator where most of the energy resides and wave forcing is very effective.

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**Figure 1.** (a) Computed power spectrum for the zonal winds at 4° latitude presented in terms of discrete Fourier harmonics,  $h$ , which are related to the frequency  $\omega = h/y$  (cpy) in units of cycles per year (y). Only the hemispherically symmetric component is shown, which dominates near the equator. The time span for the analysis is 50 years, ignoring the first 10 years to account for spin-up. With harmonic  $h = 27$ , the dominant QBO period is 22.22 months, i.e., 50/27 years. The spectral side lobes at  $h = 22$  and 32, removed from  $h = 27$  by 5 wave numbers, describe the 10-year SC modulation of the QBO. (b) To reveal the SC modulation of the QBO, the complex spectral amplitudes for  $h = 27, 22$  and 32 are synthesized. With contour interval of 2 m/s, the lowest level displayed is 8 m/s. The results show that the QBO amplitude varies over 10 years from about 10 to more than 16 m/s at 30 km, which is in qualitative agreement with the observations by Salby and Callaghan (2000). With dashed line, the phase of the SC forcing is shown. The results are identical to those discussed in Mayr et al. (2006).

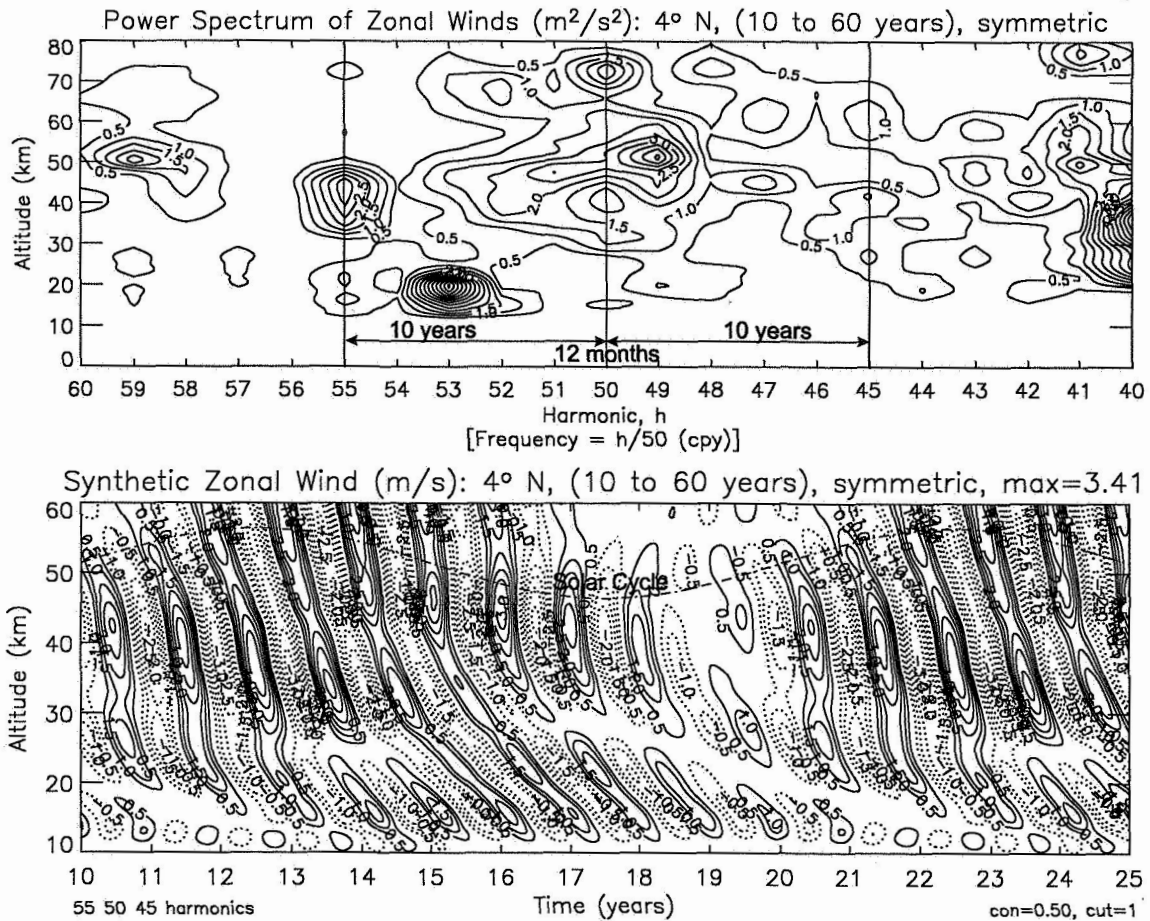
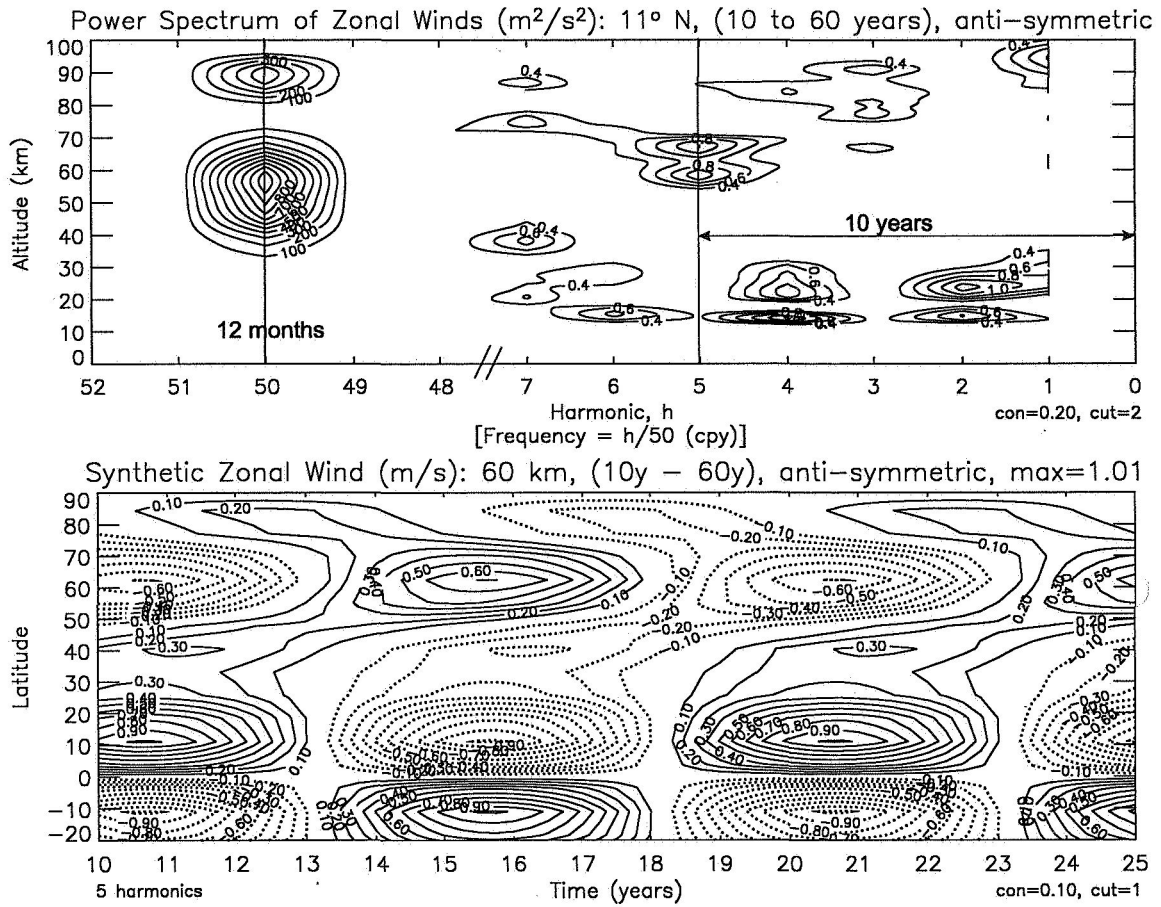
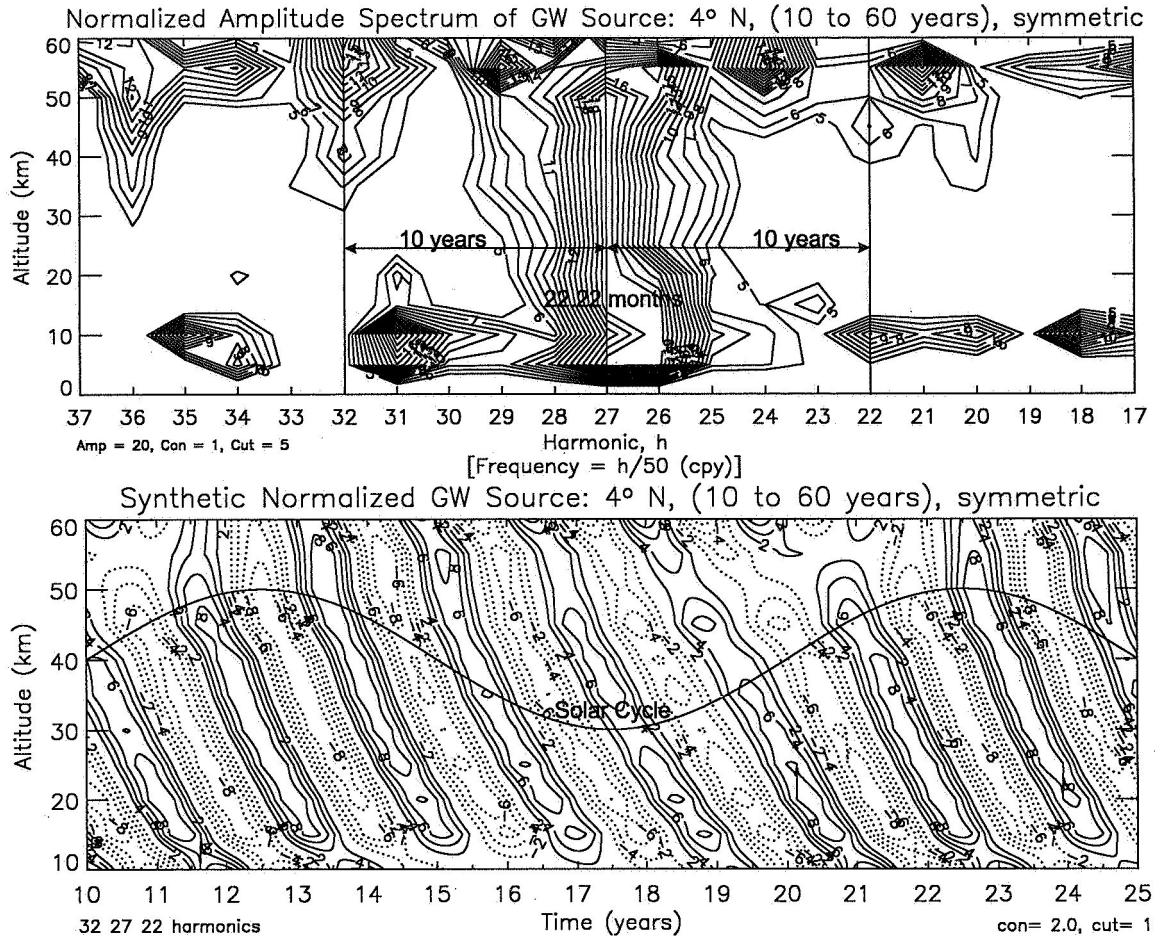


Figure 2. Similar to Figure 2 but for the computed zonal winds of the (hemispherically) symmetric annual oscillation that is confined to equatorial latitudes. (a) With  $h = 50$ , the 12-month periodicity is identified, and the spectral side lobes at  $h = 45$  and  $55$  describe the 10-year SC signature. (b) Synthesis of the harmonics  $h = 50, 45$  and  $55$  describe the modulation of the annual oscillation by the SC whose phase is shown with dashed line. Like the QBO, this symmetric oscillation slowly propagates down to lower altitudes.

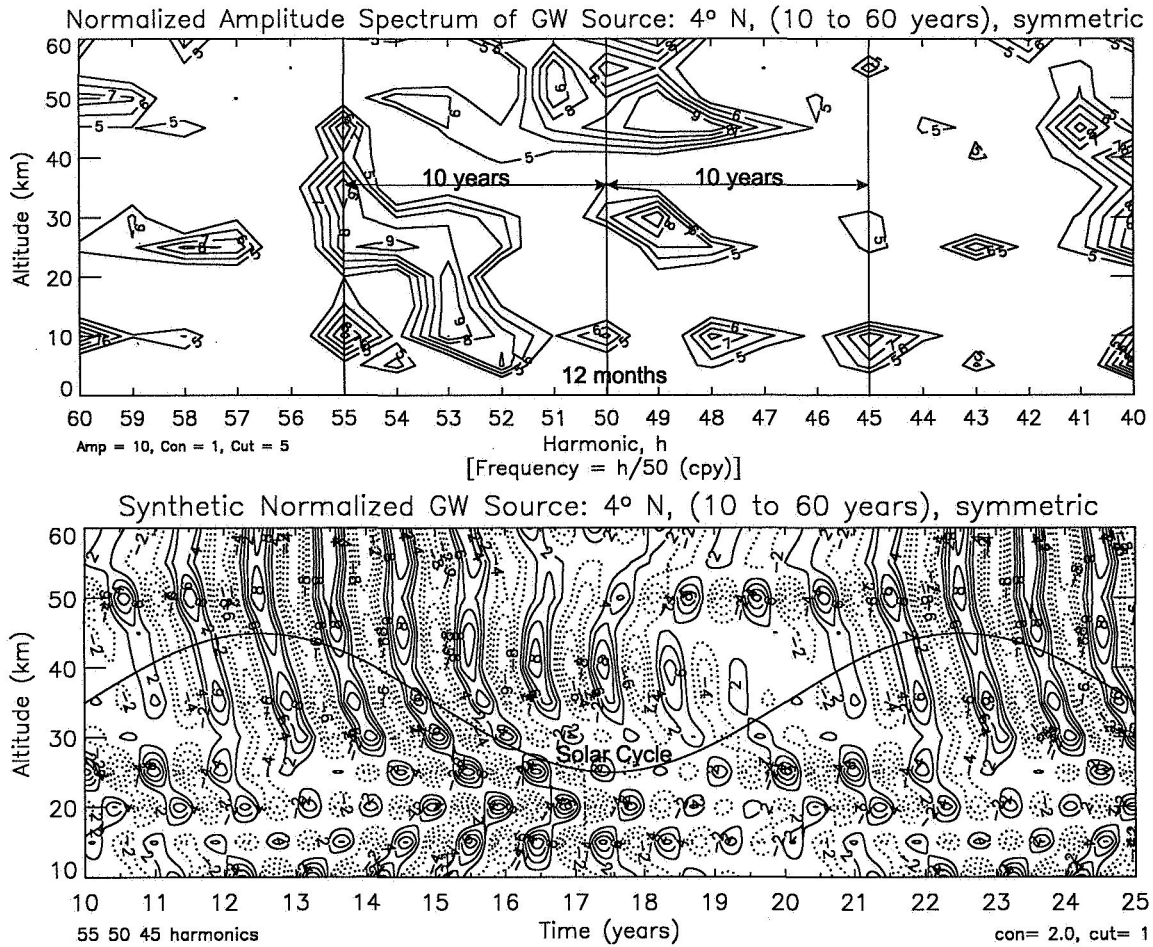


**Figure 3.** (a) Spectrum of the (hemispherically) anti-symmetric wind component, covering the harmonics  $0 < h < 7$  to reveal the 10-year SC signature that peaks at around 65 km in the mesosphere. Also displayed is the spectral feature of the dominant anti-symmetric 12-month annual oscillation (AO) at  $h = 50$ . (b) The anti-symmetric 10-year SC component at 60 km is shown to vary with latitude. It is largest at latitudes near  $10^\circ$ , where non-linear interaction with the dominant AO can produce the SC modulated symmetric AO (Figure 2) that peaks to equatorial latitudes.



**Figure 4.** Gravity wave momentum source (MS) describing the SC modulation of the QBO. Normalization is applied to eliminate the exponential variation of the MS, which still preserves the SC modulation of interest. Although the vertical resolution of the model is about 0.5 km, the MS for the present purpose is recorded with 5 km height increments to reduce the model output; the results therefore appear rugged. (a) The spectrum shows the dominant MS at  $h = 27$  (22.22 months), which generates the zonal wind oscillations shown in Figure 1. Though relatively weak, the side lobes for the 10-year SC modulation are present. (b) The synthesis for the spectral features of the SC modulated QBO at  $h = 27, 22$  and 32 shows a pronounced amplitude modulation. With contour intervals of 2 for the normalized MS, the maximum amplitudes are close to 10 (as defined by the normalization), while the minimum values are only around 6. This demonstrates that the GW source amplifies the SC modulation of the QBO, which represents a new mechanism for the solar influence on the lower atmosphere.





**Figure 5.** Similar to Figure 4 but for the normalized MS that drives the (hemispherically) symmetric annual oscillation shown in Figure 2. (a) Due to the limited height resolution of the output, the spectrum is ragged. At  $h = 50$ , the 12-month periodicity is nevertheless evident, and the spectral features at  $h = 45$  and  $55$  describe the 10-year SC signature. (b) Analogous to Figures 2, the synthesis of the harmonics  $h = 50, 45$  and  $55$  describe the MS for the SC modulation of the symmetric annual oscillation.