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### Popular Summary

An analysis is presented of the zonal wind and temperature variations supplied by the National Center for Environmental Prediction (NCEP), which have been assimilated in the Reanalysis and the Climate Prediction Center (CCP) data sets. The derived zonal-mean variations are employed. Stimulated by modeling studies, the data are separated into the hemispherically symmetric and anti-symmetric components, and spectral analysis is applied to study the annual 12-month oscillation and Quasi-biennial Oscillation (QBO). For data samples that cover as much as 40 years, the results reveal a pronounced 5-year modulation of the symmetric AO in the lower stratosphere, which is confined to equatorial latitudes. This modulation is also inferred for the temperature variations but extends to high latitudes, qualitatively consistent with published model results. A comparison between different data samples indicates that the signature of the 5-year oscillation is larger when the QBO of 30 months is more pronounced. Thus there is circumstantial evidence that this periodicity of the QBO is involved in generating the oscillation. The spectral analysis shows that there is a weak anti-symmetric 5-year oscillation in the zonal winds, which could interact with the large anti-symmetric AO to produce the modulation of the symmetric AO as was shown in earlier modeling studies. According to these studies, the 30-month QBO tends to be synchronized by the equatorial Semi-annual Oscillation (SAO), and this would explain why the inferred 5-year modulation is observed to persist and is phase locked over several cycles.

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### Abstract:

An analysis is presented of the zonal wind and temperature variations supplied by the National Center for Environmental Prediction (NCEP), which have been assimilated in the Reanalysis and the Climate Prediction Center (CCP) data sets. The derived zonal-mean variations are employed. Stimulated by modeling studies, the data are separated into the hemispherically symmetric and anti-symmetric components, and spectral analysis is applied to study the annual 12-month oscillation and Quasi-biennial Oscillation (QBO). For data samples that cover as much as 40 years, the results reveal a pronounced 5-year modulation of the symmetric AO in the lower stratosphere, which is confined to equatorial latitudes. This modulation is also inferred for the temperature variations but extends to high latitudes, qualitatively consistent with published model results. A comparison between different data samples indicates that the signature of the 5-year oscillation is larger when the QBO of 30 months is more pronounced. Thus there is circumstantial evidence that this periodicity of the QBO is involved in generating the oscillation. The spectral analysis shows that there is a weak anti-symmetric 5-year oscillation in the zonal winds, which could interact with the large anti-symmetric AO to produce the modulation of the symmetric AO as was shown in earlier modeling studies. According to these studies, the 30-month QBO tends to be synchronized by the equatorial Semi-annual Oscillation (SAO), and this would explain why the inferred 5-year modulation is observed to persist and is phase locked over several cycles.

### **1. Introduction and Background**

In the stratosphere at equatorial latitudes, the mean zonal circulation is dominated by the Quasi-biennial Oscillation (QBO) and Semi-annual Oscillation (SAO). Reviewed by Baldwin et al. (2001), the QBO has periods between 22 and 34 months and originates in the lower stratosphere (Reed, 1965); while the 6-month SAO is more important in the upper stratosphere (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 can be driven by the momentum deposition from eastward propagating Kelvin waves and westward propagating Rossby gravity waves. Later modeling studies with observed planetary waves 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 scale waves, Hamilton et al. (1995) showed that the QBO in the stratosphere 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).

In the context of this paper, we wish to remind us of the dynamical properties that control the equatorial oscillations, which were discussed by Lindzen and Holton (1968) in their seminal theory for the QBO. At low latitudes, and at the equator precisely, the Coriolis force vanishes so that the wave momentum source is dissipated only by vertical diffusion. At the equator, the meridional circulation does not come into play to redistribute the flow momentum. [To first order, the equatorial QBO thus can be described with a one-dimensional model, Lindzen and Holton referred to as “prototype model”.] Wave-mean-flow interactions are thus very efficient in generating and amplifying the equatorial zonal wind oscillations. This is evident from models

with latitude independent wave source, which produce a QBO that still peaks at the equator and is confined to low latitudes (e.g., Mengel et al., 1995).

For the wave forcing around the equator to be so effective, it is essential that the generated oscillations are hemispherically symmetric, which applies to the QBO and SAO to first order. Waves propagating up around the equator then can generate flow oscillations that tend to be in phase across the region. Phenomena that are to first order hemispherically anti-symmetric, in contrast -- primarily the 12-month annual oscillation (AO) with opposite phase in the northern and southern hemispheres -- tend to vanish at the equator. The opposite wave forcing in the opposite hemispheres is then relatively ineffective in generating coherent oscillations around the equator.

The above-discussed distinguishing characteristics of the symmetric and anti-symmetric oscillations are illustrated in a recent modeling study of the AO (Mayr et al., 2005), which has been in part the stimulus for the data analysis discussed here. Our analysis is also guided by model predictions (Mayr et al., 2000; 2003a, b), which show that the QBO -- depending on its periodicity -- can generate long-term oscillations through interaction with the seasonal cycles. In support of this prediction, we shall present observational evidence for a 5-year modulation of the AO near the equator that appears to be associated with a 30-month QBO.

## 2. NCEP Data Analysis

In our study, we employ the NCEP (National Center for Environmental Prediction) data that have been analyzed to extract the zonal mean component (Eric Nash, Science Systems and Applications Inc.). Specifically, three data sets are examined: (1) Reanalysis data covering a period of 48 years between 1958 and 2006, for which different assimilation models were used; (2) Reanalysis-2 data covering 28 years between 1978 and 2006, for which a single assimilation model was used; and (3) data from the Center for Climate Prediction (CCP), covering the years from 1978 to 2006. The Reanalysis data extend from the surface to about 31 km, while the CCP data extend to about 55 km. Both temperature and zonal wind measurements were employed in the Reanalysis data sets; but the CCP data represent temperature measurements only, and the winds were derived from that. The Reanalysis and CCP data are given respectively in latitude intervals of 2.5 and 2 degrees.

Considering the above-discussed characteristics and importance of the wave forcing, which controls the equatorial oscillations, we shall delineate for diagnostic purposes the NCEP data in terms of their hemispherically symmetric and anti-symmetric components. For this purpose, the data ( $D$ ) at a particular (and the same) latitude in the northern ( $n$ ) and southern ( $s$ ) hemispheres,  $D_n$ ,  $D_s$ , respectively are split up into the symmetric ( $S$ ) and anti-symmetric ( $A$ ) elements by computing respectively  $DS = (D_n + D_s)/2$  and  $DA_n = (D_n - D_s)/2$ ,  $DA_s = (D_s - D_n)/2$ . The original data in the two hemispheres are then reproduced by the addition of the symmetric and anti-symmetric components, i.e.,  $D_n = DS + DA_n$  and  $D_s = DS + DA_s$ . As discussed above,  $DS$  would then describe primarily the QBO and SAO that characterize the nearly symmetric atmospheric oscillations around the equator, while  $DA_n = -DA_s$  would represent to first order the dominant 12-month AO with opposite phase in the two hemispheres.

Employing different data samples, the hemispherically symmetric and anti-symmetric components are spectrally analyzed to describe the AO, QBO and long-term variations. The important spectral features are then synthesized to reveal, for comparison, the different oscillations embedded in the data. Our analysis is restricted to the stratosphere at altitudes above 10 km.



### 3. Analysis Results

The more extensive Reanalysis data cover the years from 1958 to 2006, and for ease of reference we count the years by starting with 0 in 1958. Under this notation, the time coverage goes from 0 to 48 data years, and we apply it to the analysis of the wind and temperature data.

#### 3.1. Zonal Winds

For reasons that will become clear subsequently, we present with Figure 1 the analysis results for sample A (defined in Figure 2b) from the Reanalysis data set, which is restricted to the range between 7 and 47 years. Shown in (a) is the hemispherically symmetric component of the amplitude spectrum for the zonal winds at 0 degree latitude, plotted versus altitude from 10 to 30 km. The spectrum is obtained from a Fourier analysis of the 40-year time span, and we present it in terms of the discrete harmonics,  $h$ , in the range from 0 to 60. As indicated in the figure, the frequencies (in cycle per year) are then determined by  $h/40$ , and the corresponding periods are given by  $40/h$  (in years).

In the spectrum of Figure 1a for the equator at 0 degree latitude, as expected, large amplitude signatures are apparent that describe the QBO at altitudes above 15 km. The dominant period is about 28.2 months, and the periods of 24 and 30 months are also identified. Of special interest for the present analysis is the sharp spectral feature at  $h = 40$ , which represents the 12-month AO. Also apparent is a spectral line at  $h = 32$  that peaks at about 26 km altitude. Removed by 8 wave numbers from  $h = 40$ , this is the signature of a 5-year modulation of the symmetric AO. Such a side lobe can be generated by non-linear processes that multiply in effect the dominant anti-symmetric AO with an anti-symmetric 5-year oscillation (O5). With simplified complex notation, the product between AO,  $A_{\text{exp}}[i_{\text{at}}]$ , and O5,  $O_{\text{exp}}[i_{\text{ot}}]$ , namely generates the side lobes with frequencies  $\omega_a + \omega_o$ ,  $\omega_a - \omega_o$ , and the longer one of the corresponding two periods is apparent in the spectrum.

Evidence for the involved 5-year oscillation itself is shown in Figure 1b, where we present the spectrum of the anti-symmetric component at 20 degree latitude (that component vanishes at the equator). At wave number  $h = 8$  is the signature of the 5-year oscillation, and the dominant 12-month AO appears at  $h = 40$ . The 5-year feature is weak, less than 0.5 m/s, but the anti-symmetric AO at 20 degree latitude is relatively large (about 12 m/s); the interaction between the two thus could produce the symmetric side lobe at  $h = 32$  in Figure 1a. The dominant QBO feature of 28.2 months accounts for the anti-symmetric side lobes at  $h = 23$  and 57, identified with dashed lines in Figure 1b, which produce a modulation of the AO with that period.

To show the 5-year modulation of the AO, we present in Figure 1c the latitudinal variations at 26 km obtained from a synthesis of the spectral features  $h = 40$  and 32 that are prominent in Figure 1a. Around the equator, the wind velocities vary over a period of 5 years by about 5 m/s. At higher latitudes, the winds are much larger, but the 5-year modulation is negligible when compared with the amplitude differences near the equator. Our analysis thus shows that the synthesized 5-year modulation of the symmetric AO in the zonal winds is confined to low latitudes.

As is apparent from modeling studies (Mayr et al., 2000; 2003b), and referred to above, an anti-symmetric 5-year oscillations can be generated by a symmetric 30-month QBO that interacts through wave filtering with the dominant anti-symmetric AO. The results presented in Figure 1 are consistent with that, but they are not sufficiently convincing. While the QBO in the spectrum has a 30-month component, its dominant period is 28.2 months as seen from Figure 1a.

In search of a time span that may contain a predominant 30-month QBO, we have analyzed the entire 48-years of Reanalysis data. For the equator at 31 km altitude, a running window of 30 months is applied, shifted by one day, to compute the amplitude, and the results are recorded with solid line in Figure 2a. The amplitudes around 20 m/s are variable to indicate in part that the QBO, as expected, is not phase locked. Further evidence of this variability is apparent from the result in dashed line, which was obtained from a running window of 90 months, with the 3<sup>rd</sup> harmonic applied to extract the 30-month QBO. In this case, the QBO was phase locked for 3 cycles, and the resulting amplitudes are therefore reduced in general and in particular during certain periods (e.g., between 10 and 17 data years).

Another measure of variability is presented in Figure 2b, where we record the normalized phase speed for a 30-month moving window. If the oscillation were perfectly phase locked, its phase would change by a constant value as the window is moved forward in time from day to day. The resulting gradient or equivalent phase speed depends on the period of the oscillation, and in Figure 2b it is normalized to a values of 1 for the 30-month QBO. From Figure 2b it is apparent that there are certain time spans in the data set where the phase speed deviates significantly from the norm. This is true for the initial few years, which were not included in the Data Sample A of Figure 1. The variability is also large for the years between 10 and 17. But Figure 2b shows that there is a period between about 17 and 37 years (identified with B) where the phase speed varies relatively little around one, thus indicating that the 30-month QBO is closer to being phase locked. This is also consistent with the amplitudes in Figure 2a, which are less variable during this particular time span.

Having thus identified a data stretch in which the 30-month QBO is expected to be more coherent and stable, we present with Figure 3 an analysis of the Data Sample B for comparison with Figure 1. This specifically selected and more restricted time span covers only 20 (instead of 40) years. As seen from Figure 3a, the symmetric 30-month signature now dominates the QBO, in contrast to its signature in Figure 1a that is relatively weak. Commensurate with that, the signatures of the 5-year oscillation are now also much stronger, and more ubiquitous. In particular, the 5-year side lobe that describes the modulation of the symmetric AO at  $h = 16$ , removed from  $h = 20$  by 4 wave numbers, is now much stronger at altitudes around 25 km than the corresponding one at  $h = 32$  in Figure 1a. The anti-symmetric 5-year oscillation at  $h = 4$  in Figure 3b, believed to be the cause for the symmetric modulation, is also more pronounced, and it peaks at 25 km altitude. The analysis of the NCEP data presented in Figures 3a and 3b thus provides considerable further evidence for the reality of the 5-year oscillation and especially for its connection to the 30-month QBO.

As identified, the spectra of Figure 3 show a number of other features associated with the 5-year oscillation. In Figure 3b, the weak anti-symmetric QBO and strong AO could generate in Figure 1a the symmetric features at  $h = 4$  and 12 that describe the 5-year modulation of the dominant symmetric QBO. Conversely, the symmetric 5-year oscillation in Figure 1a could generate the modulations of the anti-symmetric AO and weak QBO in Figure 3b, as indicated. However, some of these features are more likely produced by the interaction between the 30-month QBO and the AO, identified with dashed lines. Most of the spectral features shown in Figures 2a and 2b appear in the model predictions for the 30-month QBO (Mayr et al., 2000; 2003b).

The predominance of the 30-month QBO for the above-discussed period is consistent with the results obtained by Tung and Yang (1994), who had analyzed ozone data for the years from 1978 to 1991 (20 to 33 data years in our notation). As shown in Figure 3 of their paper, the QBO

of 30 months dominates around the equator. In addition to that, and away from the equator, the authors also identified the periods of 8.6 and 20 months. In our analysis, these periods are shown respectively in Figure 3b at  $h = 28$  and 12. The spectra obtained by Tung and Yang also reveal a pronounced 60-month (5-year) signature outside the tropics.

Since the anti-symmetric 5-year oscillation is at the core of the data study presented here, we show in Figure 3, for 26 km altitude, a synthesis of the harmonic  $h = 4$  plotted versus latitude and time. With opposite phase in the two hemispheres, the magnitude of the 5-year oscillation is small, about 0.5 m/s, but it could interact with the large anti-symmetric AO to produce the symmetric modulation in Figure 3a. This 5-year modulation of the AO is shown in Figure 3d. Plotted versus latitude and time, we present a synthesis of the harmonics  $h = 20$  and 16. As in Figure 1c for Data Sample A, the 5-year modulation of the AO is confined to latitudes around the equator. And the modulated oscillations in Figure 3d are in phase with those shown in Figure 1c.

[For convenience of the review, not part of the paper, we submit in the Appendix some figures taken from publications. Figure 1 of the Appendix shows the modeled 30-month QBO with 5-year modulation. In Figure 2, the spectra are shown in which the periods of 8.6, 20, 30, and 60 appear. In Figure 3, the modeled symmetric and anti-symmetric spectra are presented but with harmonics,  $h$ . In Figure 4, the proposed mechanism is illustrated, in which the 30-month QBO could generate the 5-year oscillation.]

### 3.2. Temperature Variations

In contrast to the zonal winds from the Reanalysis NCEP data, which extend only to altitudes of about 31 km, the CCP temperatures cover the entire stratosphere and go up to about 55 km. Since the latter data set covers only the years between 21 and 48, we have chosen the Sample C identified in Figure 2b. Covering a time span of 20 years, the chosen data eliminate the last few years in which the 30-month QBO is more variable according to Figure 2b.

Shown in Figure 4a is the symmetric amplitude spectrum for the temperature at 0 degree latitude, extending from 10 to 50 km altitude. As in Figure 3a, a pronounced signature is evident at  $h = 16$ , which causes the AO at  $h = 20$  to be modulated by the period of 5 years. [There is also a symmetric 5-year signature at  $h = 4$ .] In Figure 4b we present a synthesis for the harmonics  $h = 20$  and 16, which produces the altitude variations (10 to 50 km) for the 5-year modulated symmetric AO at 0 degree latitude. The oscillation propagates down with slow phase progression (about 4 km/month), which is characteristic of wave driven oscillations around the equator. [Synthesized height variations for the weaker hemispherically anti-symmetric AO near the equator (not presented) exhibit no time progression with altitude, due to the lack of efficient wave forcing.] The modulation is largest at 35 km where the AO temperature amplitude varies by 6 K over a period of 5 years. The latitudinal variation of the synthesized AO for  $h = 20$  and 16 are shown in Figure 4c at 31 km. At this altitude, the magnitude of the modulation is smaller than at 35 km, but it is still about 1 K between minimum and maximum, and it appears to be in phase with the wind oscillations in Figures 1c and 3d. As is the case for the symmetric zonal winds, the magnitude of the AO temperature amplitude increases drastically towards higher latitudes. But unlike the zonal wind oscillation, the AO temperature exhibits a large 5-year modulation at high latitudes. The difference between minimum and maximum amplitude is almost a factor of two larger at the poles than at the equator.

## **4. Discussion and Conclusion**

The anomalous annual oscillations at tropical latitudes, the subject of our paper, have been extensively documented for the observed temperatures (e.g., Reed and Vlcek, 1969; Pawson and

Fiorino, 1998). We are not aware, however, that an observed 5-year oscillation has been reported in the literature and in particular that such a feature has been tied to the 30-month QBO as was predicted (Mayr et al., 2000, 2003a, b). Our approach of delineating the observations in terms of the hemispherically symmetric and anti-symmetric components also appears to be novel.

Based on our modeling studies and the limited results from the above analysis of NCEP data, we propose that the symmetric and anti-symmetric components of the atmosphere could be valuable in diagnosing and understanding different classes of atmospheric processes. In general terms, one may look at the atmosphere under the influences of: (1) the Sun and (2) the difference between the topographies of the two hemispheres. As discussed in the above introduction, one needs to add to that the premier dynamical influence of the wave interactions around the equator that generate the QBO. To first order, this influence of wave forcing is neither tied necessarily to the Sun nor to the differences of the hemispherical topographies.

For the zonal mean, the solar influence appears essentially in the 12-month AO and 6-month SAO. The solar AO is anti-symmetric, with positive winds and temperature variations in the summer hemisphere, and the opposite in winter; while the solar (and wave driven) SAO is mainly symmetric, with zonal winds that peak at the equator. Symmetry also applies to the QBO. These basic features of the atmosphere can be reproduced qualitatively with idealized models that do not account for topography and the related differences of planetary wave activity in the two hemispheres. In realistic GCMs with realistic topographies and realistic planetary waves, the AO no longer is purely anti-symmetric owing to the solar influence only. The asymmetry between the hemispheres is then reproduced with the addition of the symmetric AO. The symmetric AO discussed thus becomes to a large extent the manifestation of the various influences that are associated with the differences between the hemispheres. And in a similar vane, such differences would account for the anti-symmetric components of the SAO and QBO.

In light of this interpretation, we propose that the observed symmetric 12-month annual oscillations of zonal winds and temperature variations (Figures 1c, 3d, 4c) have two regimes. The one at low latitudes may be understood primarily in terms of the wave forcing that drives the equatorial oscillations. The regime outside the tropics may be understood as being caused by the differences between the two hemispheres with their different planetary wave activities; and quasi-geostrophic balance between zonal winds and temperature variations may be satisfied there.

As shown in this paper, the equatorial and symmetric AO is modulated by a 5-year oscillation, which appears to be associated with a QBO that has the period of 30 months as predicted (Mayr et al., 2000, 2003a, b). It is argued in Mayr et al. (2000) that the QBO period of 30 months is well suited for synchronization by the SAO. In intervals of 15 months the positive and negative phases of the QBO and SAO can coincide [illustrated with Figure 5 of the Appendix]. We believe that this synchronization would contribute to keep the 30-month QBO phase locked, which in turn would help in generating the 5-year modulation of the AO that prevails over several cycles, as is evident from Figures 1c and 3d for the 40-year and 20-year data samples analyzed. In the 40-year data sample, the inferred (observed) 5-year modulation prevails over 8 cycles, which seems to require from the 30-month QBO that it is remarkable coherent and stable.

Tung and Yang (1994) analyzed QBO and Ozone data for the time span from 1978 to 1991 (20 to 33 data years in our notation). Their analyses thus covers a subset of the time span we have chosen for Data Sample B discussed in Figure 3. In agreement with our analysis, Tung and

Yang showed with their Figure 3 that the 30-month QBO dominates around the equator. Away from the equator, the ozone data contain pronounced signatures with periods of 8.6 and 20 months, corresponding to  $h = 28$  and  $12$  in our Figure 3b respectively, and we agree with the interpretation of these features that had been offered by Tung and Yang. Their data also reveal a pronounced 60-month signature, but it was not identified or discussed in their paper.

From Figures 1c and 3d it is apparent that the 5-year modulated symmetric AO in the zonal winds is confined to equatorial latitudes, which is consistent with the effectiveness of the wave forcing that characterizes the tropical dynamics (Lindzen and Holton, 1968) as illustrated in a recent modeling study (Mayr et al., 2005). In the corresponding temperature variations (Figure 4c), the 5-year modulation does extend to high latitudes into the Polar Regions, and this is also seen in the model results.

### Figure Captions

Figure 1: Data Sample A (defined in Figure 2b). Zonal-mean zonal winds are analyzed, which were provided by Eric Nash (Science Systems and Applications Inc.) based on Reanalysis data from the National Center for Environmental Prediction (NCEP). The data were selected for a limited time span of 40 years (i.e., 7 to 47 data years). (a) The amplitude spectrum is obtained from Fourier analysis and shows the hemispherically symmetric component at 0 degree latitude ( $L = 0$ ) plotted versus harmonics,  $h$ ; the corresponding frequencies for the 40 year time span analyzed are given by  $h/40$  in cycles per year (cpy) with periods of  $40/h$  in years. [With contour intervals of 0.3 m/s, the lowest 4 levels are suppressed to eliminate clutter.] At  $h = 40$  is the signature of the 12-month annual oscillation (AO),  $h = 20$  and  $16$  represent the 24- and 30-month QBO signatures, and the dominant QBO period of about 28.2 month appears at  $h = 17$ . Displaced by  $h = 8$  from  $h = 40$ , at  $h = 32$ , is the signature of the 5-year modulation of the AO as discussed in the main text. (b) Spectrum of hemispherically anti-symmetric component at 20 degree latitude ( $L = 20$ ) reveals the weak 5-year signature with small contour intervals of 0.05 m/s. (c) Synthesized winds at 26 km ( $A = 26$ ) for the symmetric components with harmonics  $h = 40, 32$ . The synthesis represents the 40-year average; the patterns shown thus repeat exactly in 5-year intervals over the entire time span (7 to 47 years) of the analysis.

Figure 2: (a) Amplitude of 30-month symmetric QBO at 31 km and 0 degree latitude, computed from a moving window displaced by 1 day. Solid line for the first harmonic with 30-month window; dashed line for the third harmonic with 90-month window. As expected, the 3<sup>rd</sup> harmonic amplitudes (dashed) tend to be smaller. (b) Effective phase speed for the moving 30-month QBO window normalized to one as discussed in the text. Deviations from 1 are a measure of the variability of the 30-month QBO. It shows that the QBO is highly variable during the first 5 years, then again between 12 and 16 years, and again after 37 years. The most stable time interval is between about 17 and 37 years, labeled B, and it is discussed in Figure 3

Figure 3: Data Sample B (defined in Figure 2b). The notations with harmonics,  $h$ , are analogous to those in Figure 1. With the present time span of 20 years (compared with 40 years in Figure 1), the periods associated with  $h$  are half as large (e.g.,  $h = 20$  for AO). (a) (b) Spectra show pronounced signatures of AO, 30-month QBO, and 5-year oscillation. Virtually every signature is identified to indicate that we have a reasonably good understanding how the spectral features are generated as discussed with Figure 1. Compared to Figure 1, the 5-year side lobe at  $h = 16$  (a) is 50% larger due to the stronger 30-month QBO. (c) Synthesized 5-year anti-symmetric oscillation for  $h = 4$  shows small wind velocities at 26 km; but their interaction with the strong AO could produce the symmetric side lobe in Figure 3a. (d) Synthesis describes

latitudinal variations of modulated symmetric AO at 26 km, essentially in phase with that shown in Figure 1c.

Figure 4: Sample C (defined in Figure 2b) from the CCP version of the NCEP data, chosen for the years 22 to 42. (a) Symmetric temperature spectrum for 0 degree latitude and from 10 to 50 km altitude show the AO at  $h = 20$  and the side lobe at  $h = 32$  to indicate a pronounced 5-year modulation that peaks near 35 km, analogous to the wind results in Figures 1 and 3. [With contour intervals of 0.1 K, the lowest 3 levels are suppressed to eliminate clutter.] (b) Synthesized variations versus height show the large 5-year modulation at 35 km. Note that the oscillation slowly propagates down, which is characteristic of the efficient hemispherically symmetric wave forcing near the equator. (a) Synthesized latitudinal variations of 5-year AO at 31 km, which is in phase with the corresponding zonal wind modulations shown in Figures 2c, 3d.

## References

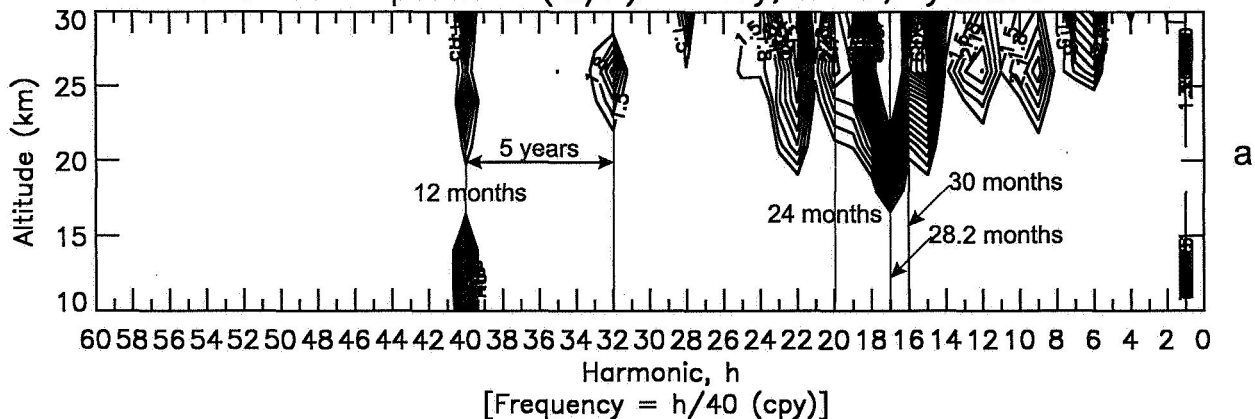
- Baldwin, M. P., Gray, L.J., Dunkerton, T.J., Hamilton, K., Haynes, P.H., Randel, W.J., Holton, J.R., Alexander, M.J., Hirota, I., Horinouchi, T., Jones, D.B.A., Kinnerson, J.S., Marquardt, C., Sato, K., and Takahashi, M., The Quasi-Biennial Oscillation, *Reviews of Geophysics*, **39**, 179, 2001.
- Baldwin, M.P., and Dunkerton, T.J., Biennial, quasi-biennial, and decadal oscillations of potential vorticity in the northern stratosphere, *J. Geophys. Res.*, **103**, 3919, 1998.
- Chan, K.L., Mayr, H.G., Mengel, J.G., and Harris, I., A 'stratified' spectral model for stable and convective atmospheres, *J. Comput. Phys.*, **113**, 165, 1994.
- Dunkerton, T.J., On the role of the Kelvin wave in the westerly phase of the semiannual zonal wind oscillation, *J. Atmos. Sci.*, **36**, 32, 1979.
- Dunkerton, T.J., A two-dimensional model of the quasi-biennial oscillation, *J. Atmos. Sci.*, **42**, 1151, 1985.
- Dunkerton, T.J., and Baldwin, M. P., Modes of interannual variability in the stratosphere, *Geophys. Res. Lett.*, **19**, 49, 1992.
- Forbes, J. M., and H. B. Garrett, Thermal excitation of atmospheric tides due to insolation absorption by O<sub>3</sub> and H<sub>2</sub>O, *Geophys. Res. Lett.*, **5**, 1013, 1978.
- Giorgetta, M. A., E. Manzini, and E. Roeckner, Forcing of the quasi-biennial oscillation from a broad spectrum of atmospheric waves, *Geophys. Res. Lett.*, **29**, 10.1029/2002GL014756, 2002.
- Hamilton, K., On the Quasi-decadal modulation of the stratospheric QBO period, *J. Clim.*, **15**, 2562, 2002.
- Hamilton, K., Dynamics of the stratospheric semi-annual oscillation, *J. Meteorol. Soc. Jpn.*, **64**, 227, 1986.
- Hines, C.O., Doppler-spread parameterization of gravity-wave momentum deposition in the middle atmosphere, 1, Basic formulation, *J. Atmos. Solar Terr. Phys.*, **59**, 371, 1997a.
- Hines, C.O., Doppler-spread parameterization of gravity-wave momentum deposition in the middle atmosphere, 2, Broad and quasi monochromatic spectra, and implementation, *J. Atmos. Solar Terr. Phys.*, **59**, 387, 1997b.
- Hirota, I., Observational evidence of the semiannual oscillation in the tropical middle atmosphere - a review, *Pure Appl. Geophys.*, **118**, 217, 1980.
- Hitchman, M.H., and Leovy, C.B., Estimation of the Kelvin wave contribution to the semiannual oscillation, *J. Atmos. Sci.*, **45**, 1462, 1988.
- Holton, J.R., and Lindzen, R.S., An updated theory for the quasi-biennial cycle of the tropical stratosphere, *J Atmos. Sci.*, **29**, 1076, 1972.
- Holton, J.R., and Tan, H.C., The influence of the equatorial quasi-biennial oscillation on the global circulation, at 50 mb, *J. Atmos. Sci.*, **37**, 2200, 1980.
- Labitzke, K., On the interannual variability of the middle stratosphere during northern winters, *J. Meteorol. Soc. Jpn.*, **60**, 124, 1982.
- Labitzke, K., Sunspots, the QBO and stratospheric temperature in the north polar region, *Geophys. Res. Lett.*, **14**, 135, 1987.
- Labitzke, K., and Van Loon, H., Association between the 11-year solar cycle, the QBO and the atmosphere. Part I: the troposphere and stratosphere in the northern hemisphere in winter, *J. Atm. Terr. Phys.*, **50**, 197, 1988.
- Labitzke, K., and Van Loon, H., On the association between the QBO and the extratropical stratosphere, *J. Atm. Terr. Phys.*, **54**, 1453, 1992.

- Lindzen, R.S., and Holton, J.R., A theory of the quasi-biennial oscillation, *J. Atmos. Sci.*, **25**, 1095, 1968.
- Mayr, H.G, Mengel, J.G., Reddy, C. A., Chan, K.L., Porter, H.S., Properties of QBO and SAO generated by gravity waves, *J. Atmos. Solar Terr. Phys.*, **62**, 1135, 2000.
- Mayr, H.G, Mengel, J.G., Drob, D.P., Chan, K.L., Porter, H.S., Modeling studies with QBO: I, Quasi decadal oscillation, *J. Atmos. Solar Terr. Phys.*, **65**, 887, 2003a.
- Mayr, H.G, Mengel, J.G., Drob, D.P., Chan, K.L., Porter, H.S., Modeling studies with QBO: II, Solar cycle effect, *J. Atmos. Solar Terr. Phys.*, **65**, 901, 2003b.
- Mayr, H.G, Mengel, J.G., and Wolff, C.L., Wave-driven equatorial annual oscillation induced and modulated by the solar cycle, *Geophys. Res. Lett.*, **32**, L20811, 2005.
- Mengel, J.G., Mayr, H.G., Chan, K.L., Hines, C.O., Reddy, C.A., Arnold, N.F., and Porter, H.S., Equatorial oscillations in the middle atmosphere generated by small scale gravity waves, *Geophys. Res. Lett.*, **22**, 3027, 1995.
- Nash, E. R., Newman, P. A., Rosenfield, J. E., and Schoeberl, M. R., An objective determination of the polar vortex using Ertel's potential vorticity, *J. Geophys. Res.*, **101**, 9471, 1996
- Pawson, S., and Fiorino, M., A comparison of reanalysis in the tropical stratosphere. Part 1: thermal structure and annual cycle, *Clim. Dyn.*, **14**, 631, 1998.
- Plumb, R.A., The interaction of two internal waves with the mean flow: Implications for the theory of the quasi-biennial oscillation, *J. Atmos. Sci.*, **34**, 1847, 1977.
- Reed, R.J., The quasi-biennial oscillation of the atmosphere between 30 and 50 km over Ascension Island, *J. Atmos. Sci.*, **22**, 331, 1969.
- Reed, R.J., and Vlcek, C. L., The annual temperature variation in the tropical lower stratosphere, *J. Atmos. Sci.*, **26**, 163, 1965.
- Salby, M., and Callaghan, P., Connection between the solar cycle and the QBO: The missing link, *J. Clim.*, **13**, 2652, 2000.
- Strobel, D.F., Parameterization of atmospheric heating rate from 15 to 120 km due to O<sub>2</sub> and O<sub>3</sub> absorption of solar radiation, *J. Geophys. Res.*, **83**, 7963, 1978.
- Takahashi, M., Simulation of the quasi-biennial oscillation in a general circulation model, *Geophys. Res. Lett.*, **26**, 1307, 1999.
- Tung, K. K., and H. Yang, Global QBO in circulation and Ozone. Part I: Reexamination of observational evidence, *J. Atmos., Sci.*, **51**, 2699, 1994.
- Zhu, X., Radiative cooling calculated by random band models with S-1-beta tailed distribution, *J. Atmos., Sci.*, **46**, 511, 1989.

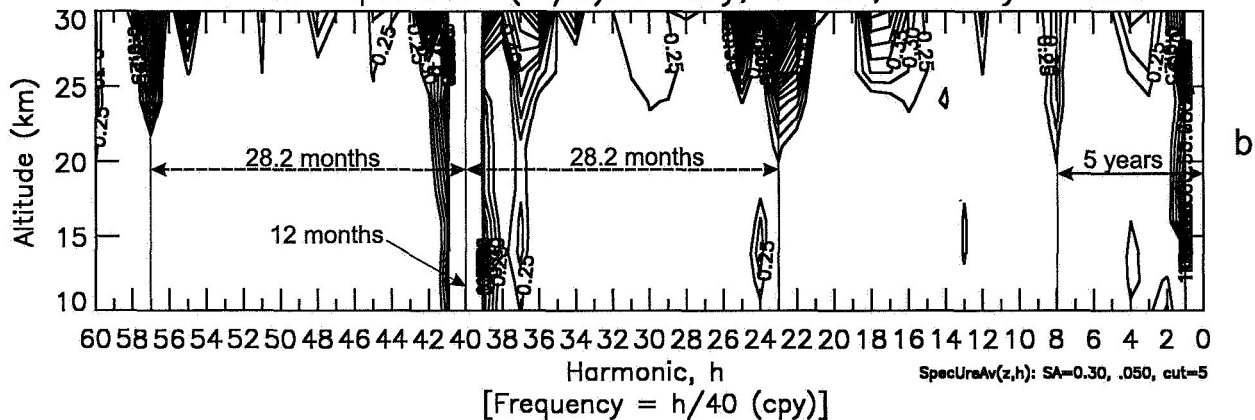


### Data Sample A

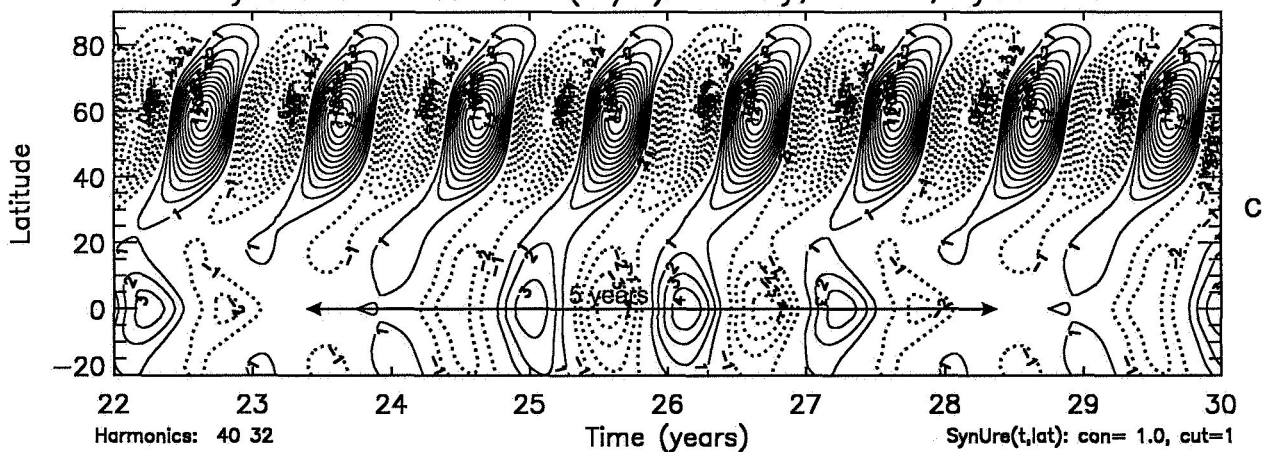
Zonal Wind Spectrum (m/s): 7-47y, L= 0, symmetric



Zonal Wind Spectrum (m/s): 7-47y, L= 20, anti-symmetric



Synthetic Zonal Wind (m/s): 7-47y, A= 26, symmetric



F ur 1

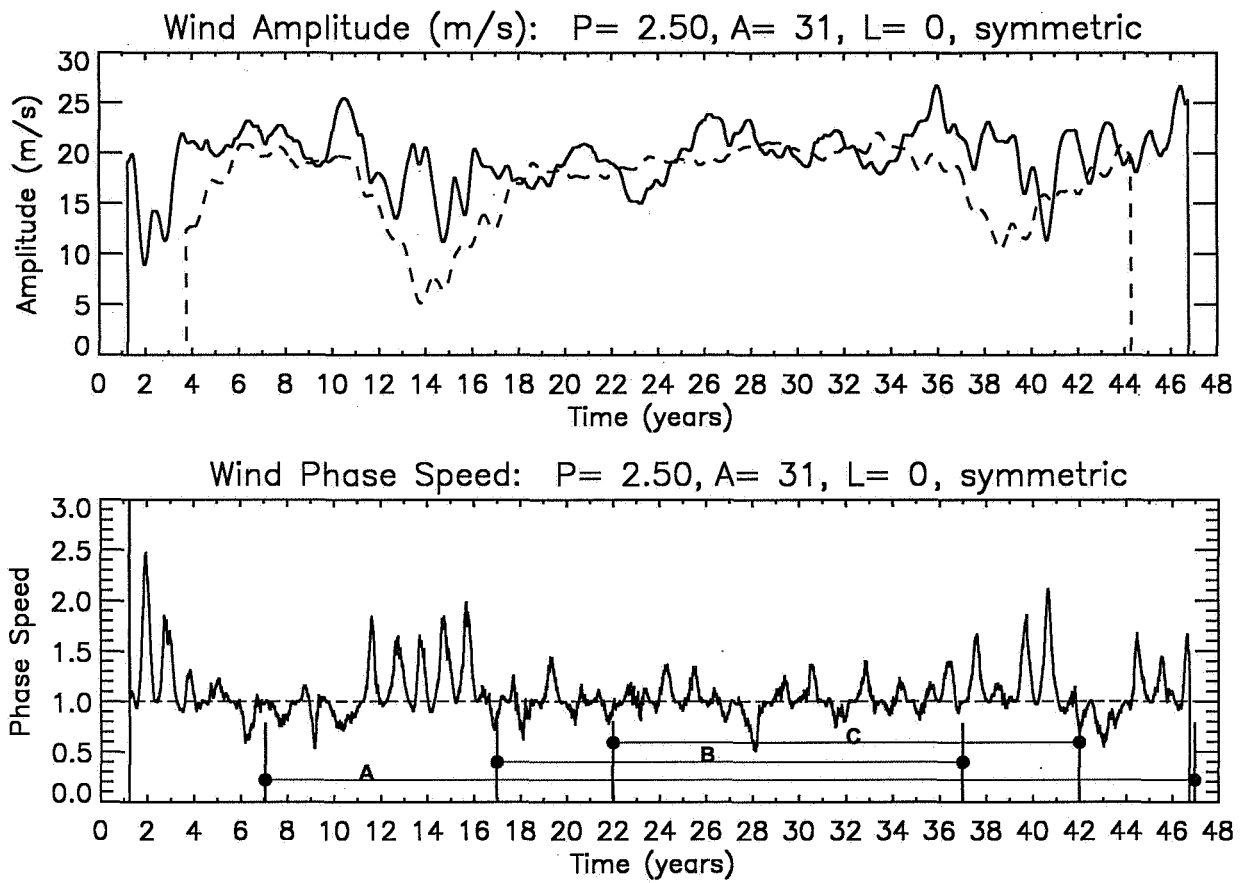
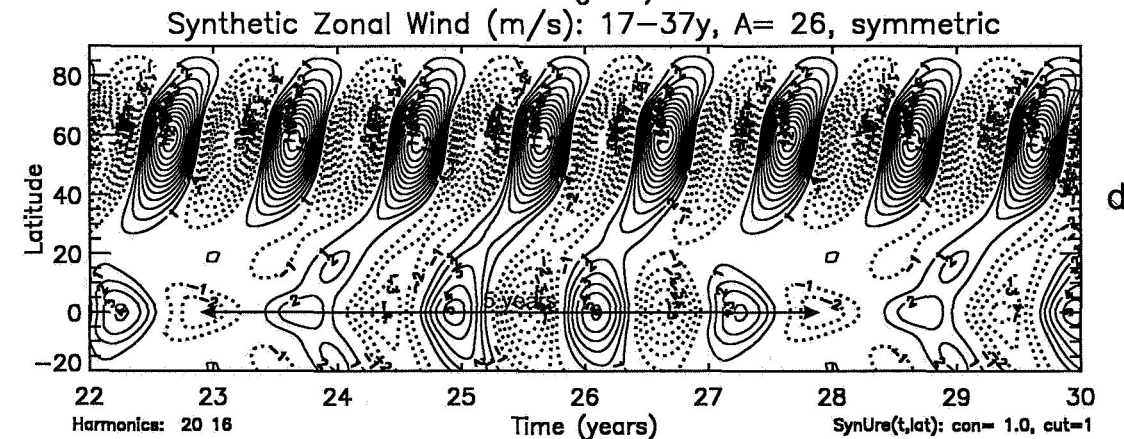
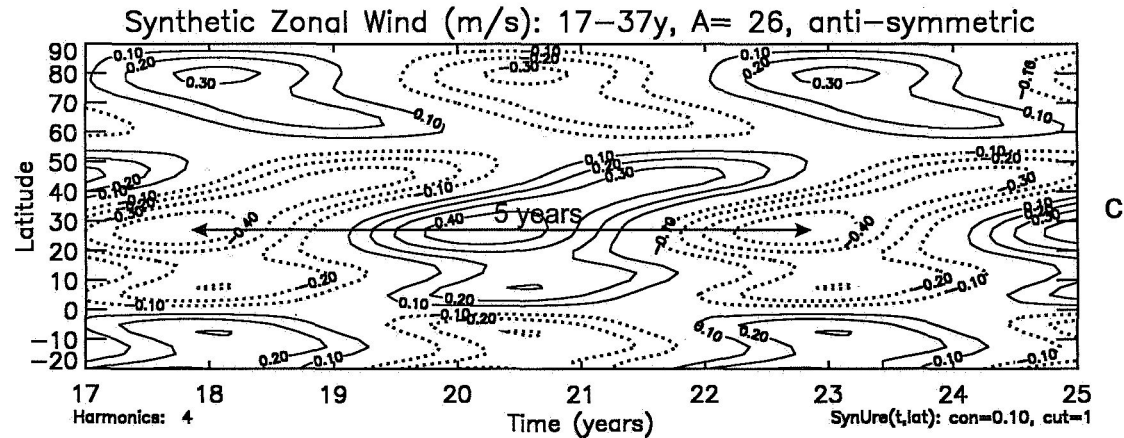
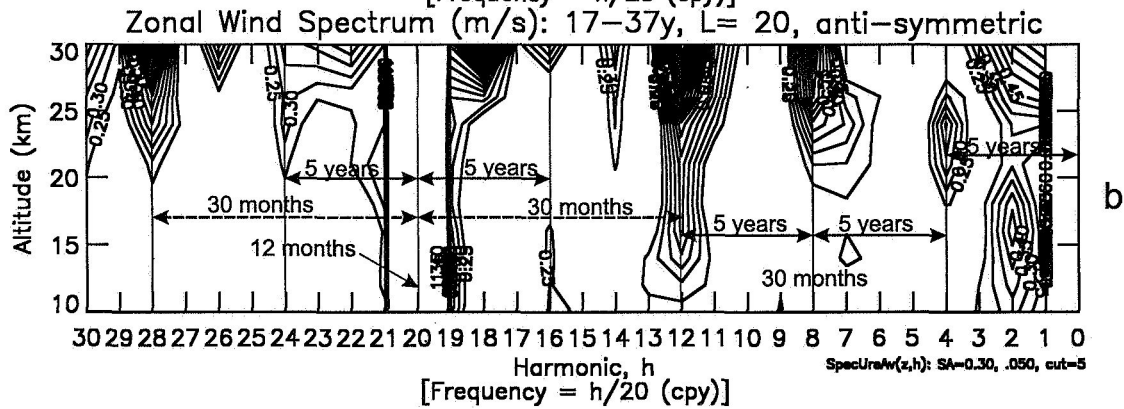
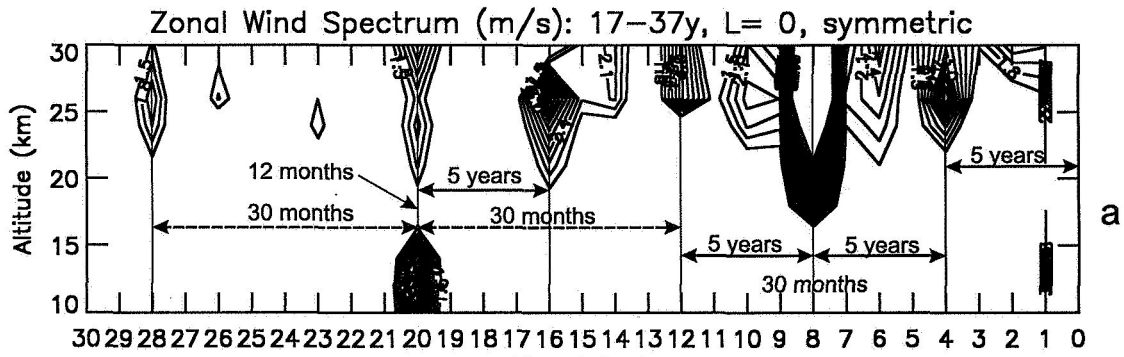


Figure 2

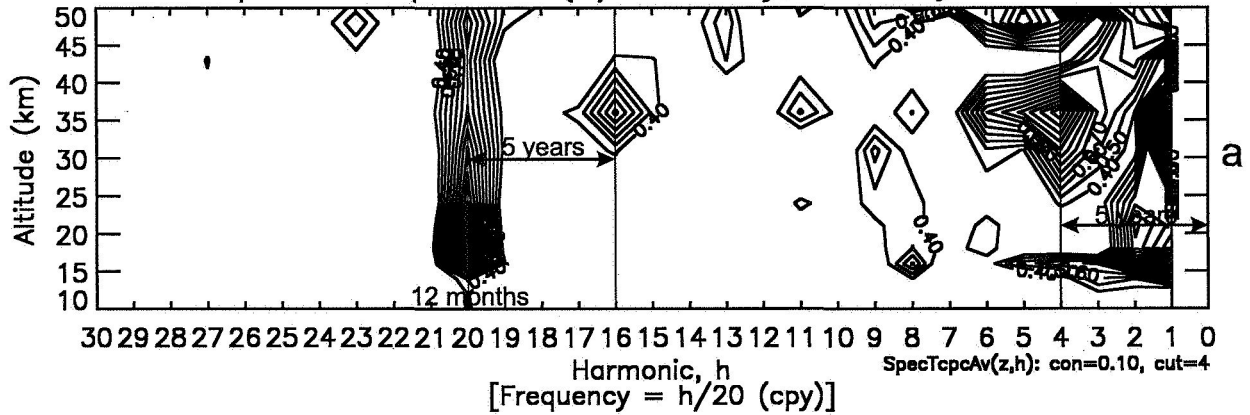
# Data Sample B



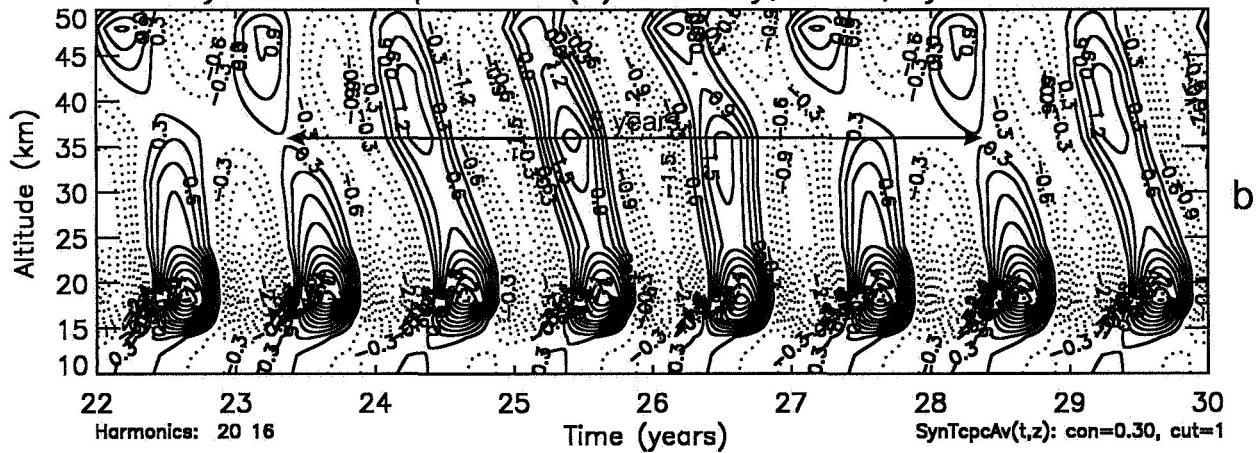
F ur 3

# Data Sample C

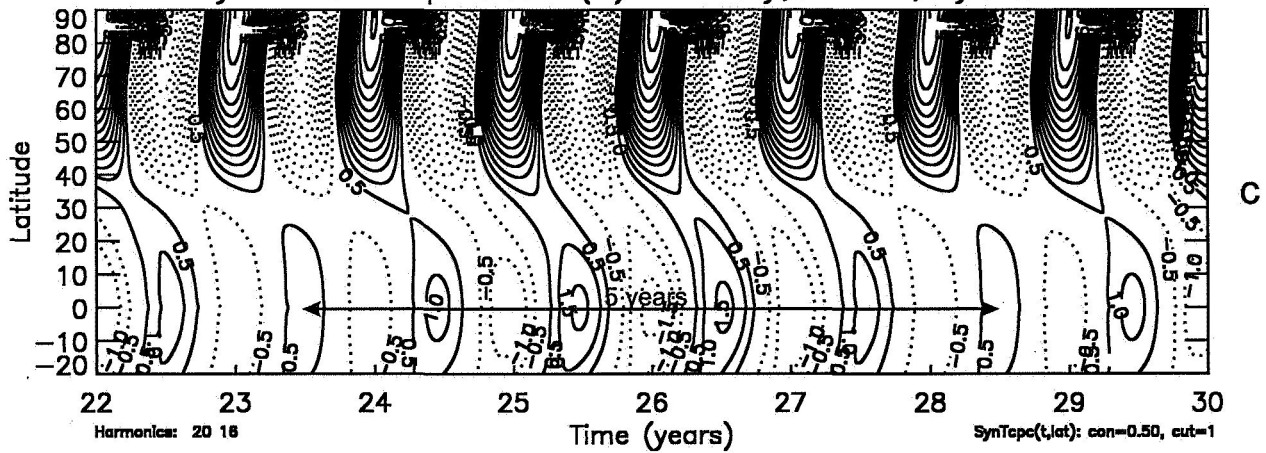
Temperature Spectrum (K): 22–42y, L= 0, symmetric



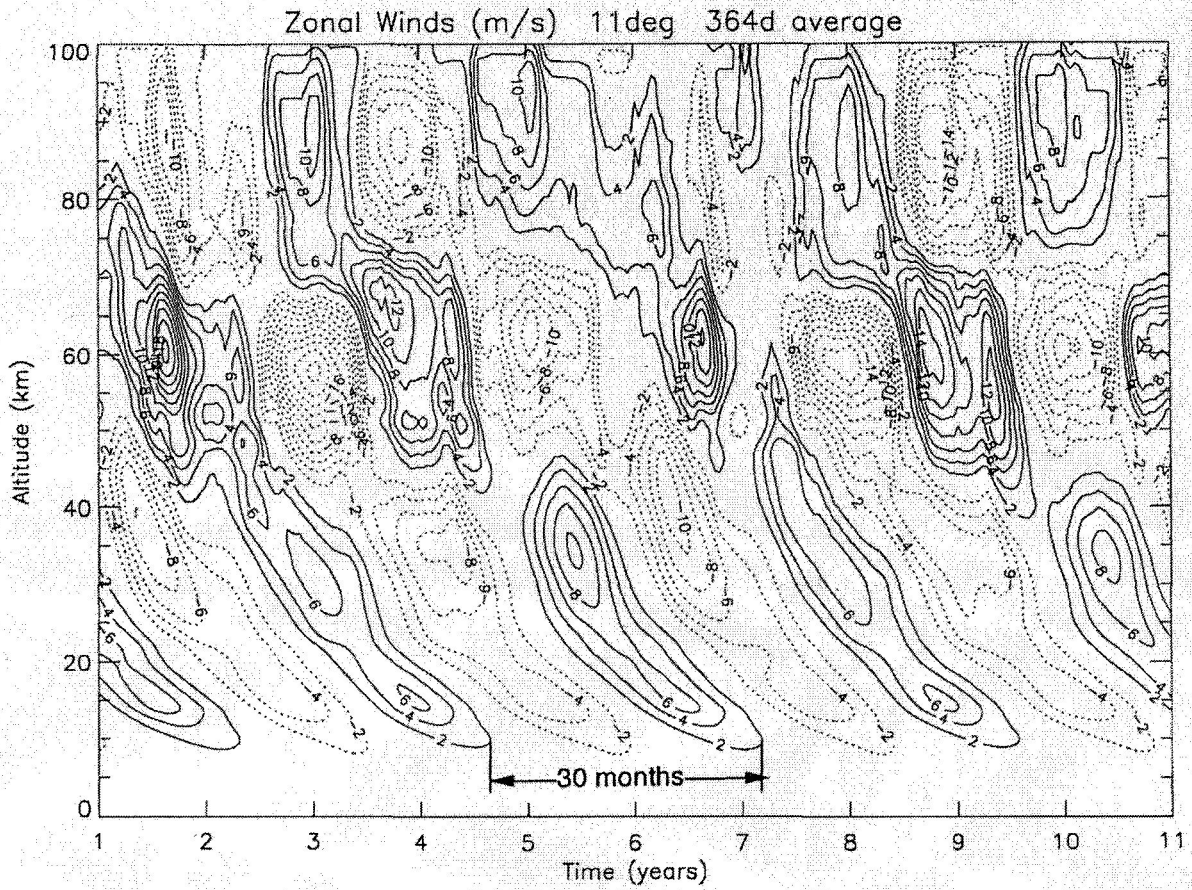
Synthetic Temperature (K): 22–42y, L= 0, symmetric



Synthetic Temperature (K): 22–42y, A= 31, symmetric

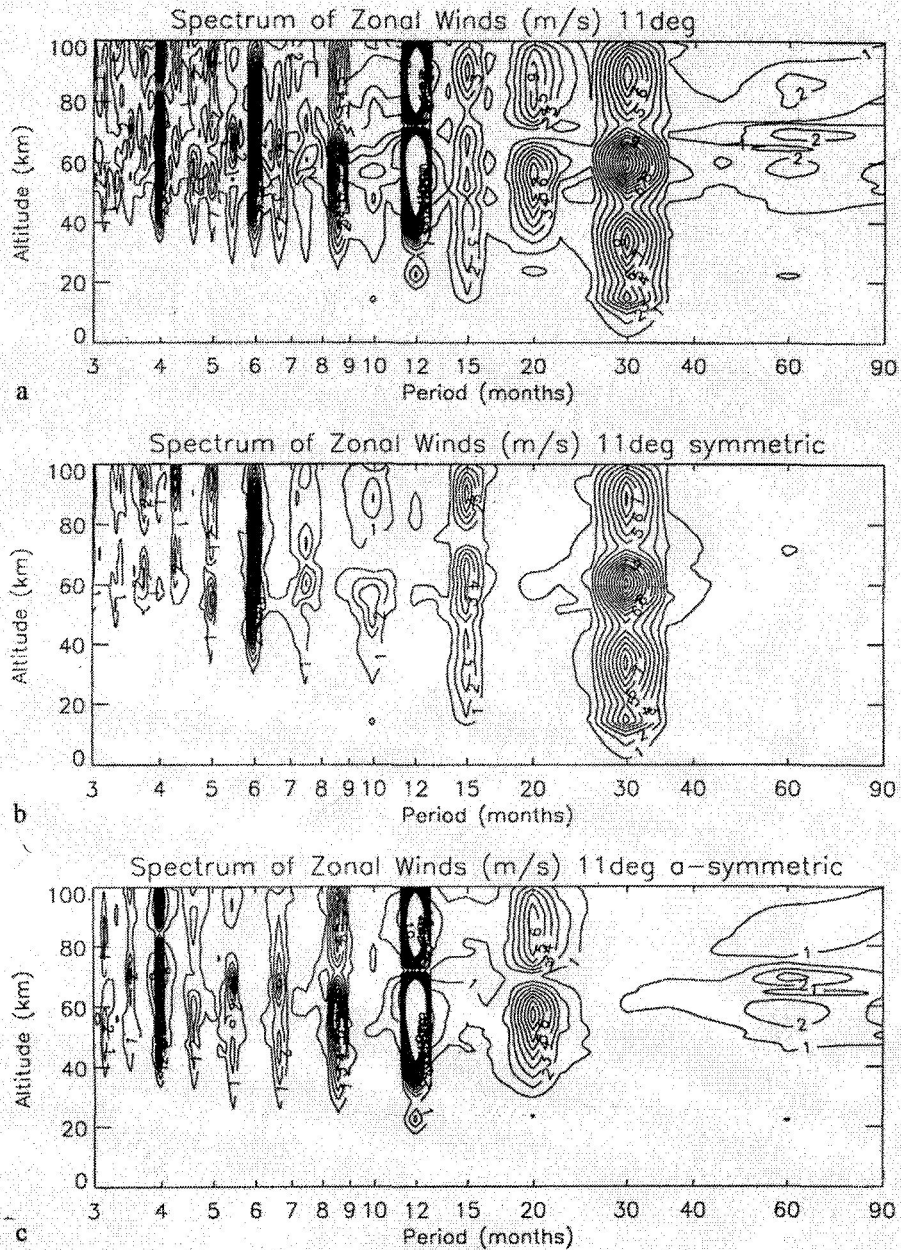


F ur



Appendix Figure 1

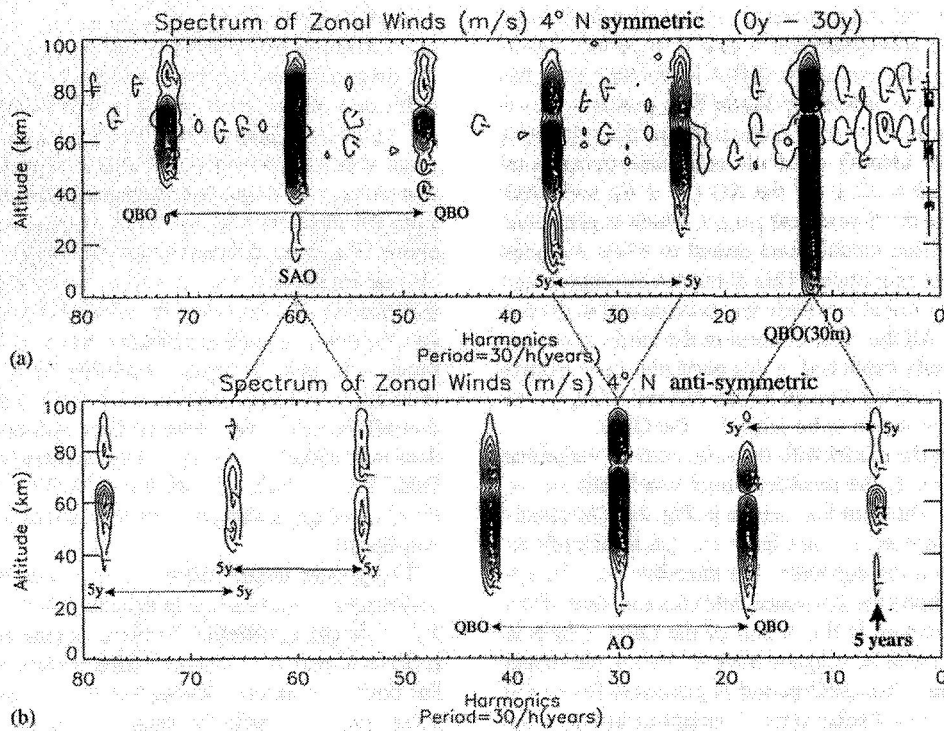
Yearly average of modeled zonal winds at 11 degree latitude show 30-month QBO, with indication of 5-year (60-month) modulation, taken from Mayr et al. (2000).



Appendix Figure 2

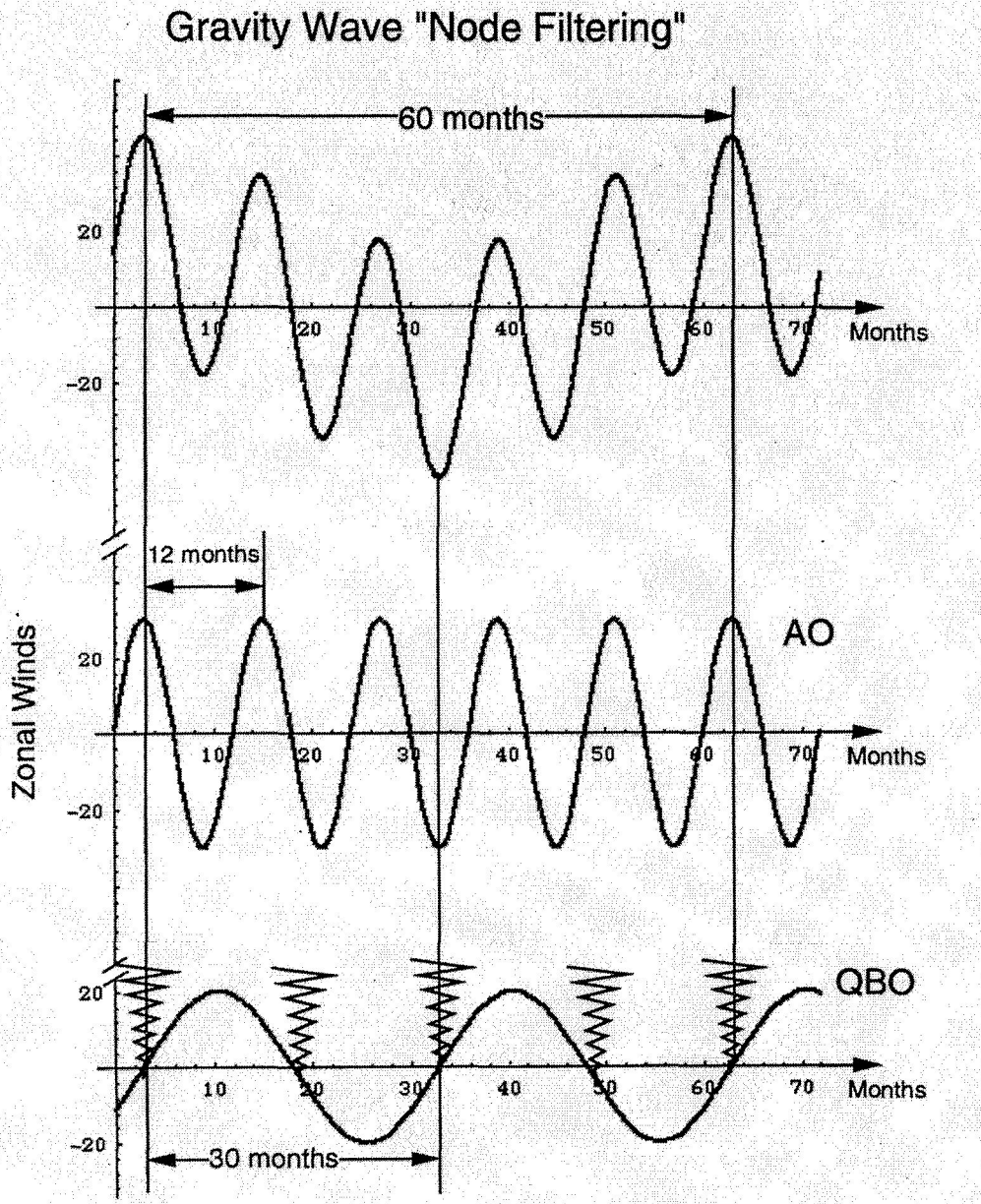
Amplitude spectrum of zonal winds at 11 degrees latitude: (a) Total (symmetric and anti-symmetric), (b) symmetric, (c) anti-symmetric. Note the dominant QBO period of 30 months in (a), and the periods of 8.6 and 20 months, and the 60-month oscillation in (c), taken from Mayr et al. (2000).





**Appendix Figure 3**

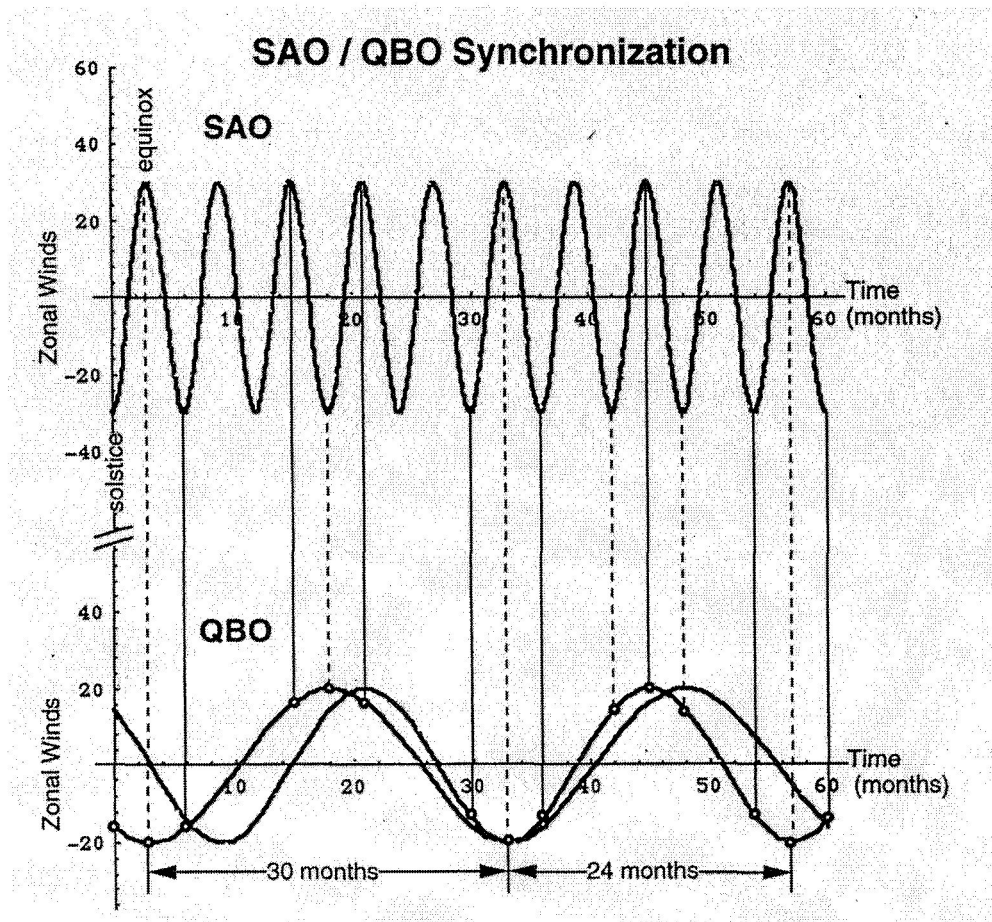
Spectrum of zonal winds at 4 degrees latitude but with harmonics, h, instead of periods. The spectral lines are identified and reproduce exactly the periods in Figure 2 of the appendix, taken from Mayr et al. (2003b).



Appendix Figure 4

Schematic illustrating the process proposed to generate the 60-month oscillation through interaction between the symmetric 30-month QBO and the anti-symmetric AO, taken from Mayr et al. (2000).





Appendix Figure 5

Proposed synchronization of the 30-month QBO by the 6-month SAO, taken from Mayr et al. (2000). As indicated with solid lines, the SAO is in phase around the maxima and minima of the 30-month QBO to facilitate the optimum synchronization, in contrast to the situation with the 24-month QBO that is less suitable for that.