Quasi-decadal Oscillations Generated by the QBO

H. G. Mayr, J. G. Mengel[2], D. P. Drob[3], H. S. Porter[4], and K. L. Chan[5]
[1] Goddard Space Flight Center, Greenbelt, MD
[2] Science Systems & Applications, Inc. Lanham, MD
[3] Naval Research Laboratory, Washington, DC
[4] Furman University, Greenville, SC
[5] University of Science and Technology, Hong Kong, China

Prepared for Submission

to

Journal of Atmospheric and Solar Terrestrial Physics

September, 2001

Abstract. Quasi-decadal oscillations (QDO) have been observed in the stratosphere and have been linked to the equatorial Quasi-Biennial Oscillation (QBO) and to the 11-year solar activity cycle. With the use of a 2D version of our Numerical Spectral Model (NSM) that incorporates Hines' Doppler Spread Parameterization (DSP) for gravity waves (GW), we demonstrate that beat periods between 9 and 11 years can be generated by the QBO as it interacts through GW filtering with the Annual Oscillation (AO) and Semi-annual Oscillation (SAO). Results are discussed from computations covering up to 50 years, and our analyses leads to the following conclusions. The QDO as a stand-alone signature is largely confined to the upper mesosphere. Its largest signature appears in the form of amplitude modulations of the QBO, AO and SAO, and these extend into the lower stratosphere. The downward control that characterizes the QBO apparently comes into play, and the longer time constants for diffusion and radiative loss at lower altitudes facilitate the QDO response. Although excited by the QBO, which is confined to low latitudes, the QDO is shown to extend to high latitudes. The effect is particularly large for the QBO with period around 33.5 month (near the upper limit of observations), which interacts with the SAO to produce a hemispherically symmetric QDO. Our analysis indicates that the QDO is transferred to high latitudes by the meridional circulation, which prominently exhibits this periodicity particularly in the amplitude modulation of the AO.

1. Introduction

Following a study by Holton and Tan (1980) that revealed an influence of the phase of the Quasi-Biennial Oscillation (QBO) on the dynamics of the stratosphere, 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 solar cycle activity when the QBO was in its negative and positive phase respectively. And opposite correlations they observed at mid latitudes. These findings have been essentially confirmed by Naito and Hirota (1997). In the northern stratosphere and for the period between 1964 and 1994, Dunkerton and Baldwin (1992) and Baldwin and Dunkerton

(1998) found evidence of a quasi decadal oscillation that correlated with the Quasi Biennial Oscillation (QBO) and solar cycle.

With the use of a 2D model, we shall demonstrate that quasi decadal oscillations (QDO) can be generated by the QBO as it interacts with the annual oscillation (AO) and semi-annual oscillation (SAO) through wave filtering.

2. Mechanism for Long-period Oscillations

The mechanism for generating long-period oscillations related to the QBO in the atmosphere has been described by Mayr et al. (2000). It was shown there that a QBO period of 30 months generates a beat period of 5 years through GW node filtering that involves the Annual Oscillation (AO, with 12-months period). We illustrate the process in Figure 1. For a given QBO period, τ_Q, in months, the GW's propagating up through the nodes of this oscillation are less attenuated and thus carry the QBO imprint. When these QBO nodes, occupying enhanced GW fluxes, are aligned with opposite phases of the AO or Semiannual Oscillation (SAO, with 6-months period), these phases are enhanced to produce half of the beat period, τ_B. This means that the condition

$$2N * \tau_Q = (2n+1) * 12,\ 6 = \tau_B \qquad (1a)$$

needs to be satisfied, where N and n are integers, or

$$E * \tau_Q = O * 12,\ 6 = \tau_B, \qquad (1b)$$

where E and O are even and odd integers respectively. One can readily verify then that according to this rule, for example, QBO periods of 30, 27, 33, and 34.5 months produce beat periods of 5, 9, 11, and 11.5 years respectively as indicated in Figure 1.

A more comprehensive picture of the relationship between QBO period and resulting beat period is presented in Figure 2, where N is the order of τ_Q that appears in Eq. (1a) and Figure 1. With the square symbol we denote beat periods produced by QBO interactions with the AO. Since the QBO is hemispherically symmetric (with the same phase in opposite hemispheres) and the AO is asymmetric (with opposite phases in opposite hemispheres), the resulting beat oscillation is also asymmetric. With the plus symbol we denote beat periods produced by interactions with the SAO, and since that is hemispherically symmetric, the beat oscillation is symmetric as well.

The beat periods of 3 and 5 years, which are associated with QBO periods of 18 and 30 months, have been discussed by Mayr et al. (1998) and Mayr et al. (2000) respectively, and they are shown with heavier but regular size square symbols in Figure 2. The heavier but larger size symbols in Figure 2 denote beat periods around 10 years, which are the results of numerical experiments discussed in this paper.

As is evident from the above analysis and Figure 2, the long-period oscillations associated with the QBO represent a discrete ensemble of symmetric and asymmetric modes that do not vary steadily with the QBO period. For QBO's in the range between 24 and 34 months, lower order (N) beat periods around 10 years can be generated but these are interspersed with beat periods around 5 years. The QBO and related beat periods being discrete, it is in the nature of the mechanism that the ability to generate a quasi-decadal oscillation will to some extent depend critically on the QBO period, how close that is to satisfy the filtering condition of Eq. (1). To demonstrate the mechanism with a numerical model thus requires some tuning, which leaves open the question how the required condition is satisfied in the real world. Related to that is the order (N) of QBO periods involved that is bound to affect the outcome significantly. This is true in particular considering that the interactions involved are non-linear, and strongly non-linear, due to feedback mechanisms that can generate a quasi chaotic component. Thus it will be more difficult, and less likely, for a high order (N) QBO interaction to be aligned with a 6-months SAO than for a low order QBO to be aligned with a 12-months AO.

3. Numerical Model

We employ here a 2D version of our Numerical Spectral Model (NSM), which incorporates the Doppler Spread Parameterization for gravity waves (Hines (1997a, b). The numerical design of this model was described by Chan et al. (1994), and its application to the middle atmosphere and lower thermosphere has been discussed in detail by Mayr et al. (1997, 2000)

The NSM is time dependent and nonlinear. But the NSM is simplified by applying perturbation theory to compute the wind fields and the temperature and density variations of the adopted globally-averaged background atmosphere. This formulation has the advantage that the radiative energy loss from the atmosphere below 120 km can be formulated in terms of Newtonian cooling. The NSM describes the atmosphere extending from the ground into the thermosphere, so that the boundary conditions are well defined. In the present application, the upper boundary is at 250 km, which is well above the region of primary interest. The vertical integration step is typically about 0.5 km and the maximum meridional wave number is $l = 12$ (12 Gaussian points per hemisphere). Depending on the chosen model parameters, the time integration step varied between 5 and 15 minutes.

The Doppler Spread GW Parameterization (DSP) of Hines (1997a, b) deals with a spectrum of waves that interact with the background wind field. It also accounts for the non-linear interactions between the waves, which affects the wave-mean flow interaction significantly. The GW momentum flux in each of the four cardinal directions is proportional to the characteristic horizontal wave number $(100\ \text{km})^{-1} \leq k_* (10\ \text{km})^{-1}$ and σ_{hi}^3, where σ_{hi} is the horizontal wind variability at the initial height taken to be the ground. For the numerical results to be discussed here, different values were chosen for these physical parameters, and we shall quote them. The GW momentum deposition in the DSP also involves so called fudge factors, which are simply chosen from the middle of the recommended range. The DSP also produces eddy diffusion rates, K, that tend to increase with altitude in relation to the rate of momentum deposition (per unit mass).

4. Model Results

To make a convincing case for the model to generate decadal oscillations, numerical experiments with multi-year integrations have to be performed that cover at least three cycles. The computational demands are thus considerable, and we must restrict ourselves to two examples that were suitable to demonstrate the mechanism. One is derived from a QBO with a period very close to 27 months as highlighted in Figure 2. This is an ideal example, and it reproduces the beat periods of 4.5, 9 and 13.5 years that are expected theoretically. The other example is derived from a QBO with a period of about 33.5 months. As shown in Figure 2, this QBO period is not ideal since it does not closely conform with the required filtering condition. But it does produce a beat period around 10 years, and the oscillation is hemispherically symmetric (in contrast to the 27-months QBO that produces an asymmetric oscillation).

4.1. QBO with 27-month Period

For this experiment, the GW parameters are chosen to be $k_* = (60 \text{ km})^{-1}$ and $\sigma_{hi} = 2$m/s at 20 km. The GW's are released at the surface, independent of latitude and season, and they carry the same momentum in the four cardinal directions (to the east, west, north, and south). To reduce the feedback from the seasonal variations to the QBO, to produce a more stable period, the solar input was reduced by about 20% so that the zonal winds at mid latitudes (eastward in winter and westward in summer) are only around 40 m/s. We have also run the model with larger heat source, and in that case (not shown) the 9-year beat period also appears, but this solution is noisier than that presented here.

Allowing for sufficient spin-up time, we present in Figure 3 the zonal winds at 20, 40, and 60 km, computed at 4° N over a time span from 3 to 25 years. As seen from this, a periodicity of 9 years is clearly evident. Distinct features such as those between 7 and 9 years and then again between 16 and 18 years are apparent at 60 and 40 km. And at 20 km, virtually every detail in the zonal winds between 5 and 14 years appears again in the next following cycle. The picture is more complicated in Figure 4, where we present a contour plot (with 10 m/s intervals) of the computed zonal winds at 4° N extending up to 100 km. Again, a number of distinct features are apparent that reappear 9 years later.

To provide analytical detail and understanding about the 9-year periodicity, we present in Figure 5 the spectrum of the zonal winds computed for a time span of 27 years at 4° N. The spectrum is presented in terms of harmonics, delineated into the hemispherically symmetric and asymmetric components, with the AO (12 months), SAO (6 months) and QBO (in months, m) identified, and the beat periods given in years (y).

As expected, the strongest spectral features in Figure 5 are those for the asymmetric AO and the symmetric SAO and QBO. By comparison, the amplitudes of the beat periods are relatively small. But one can readily show that these beat periods appear also in other prominent features of the spectrum, which proves to be rather rich as Figures 3 and 4 already indicated. For example, the 9-year periodicity appears in the lobe harmonics (9, 15), which are produced through the interaction with the QBO, i.e., 12 ± 3. Since the QBO is symmetric and the 9-year oscillation is asymmetric, the resulting lobes also are asymmetric. A synthesis of the harmonics 9, 12 and 15 is presented in Figure 6a and reveals the 9-year modulation of the QBO extending down to 20 km. In a similar vane, one can explain the harmonics (24, 30) as the product of the 9-year oscillation interacting with the AO, i.e., 27 ± 3, and in Figure 6b we present a synthesis of the harmonics (24, 27, 30) that reveal the resulting modulation of the annual cycle. Superposition of Figures 6a and 6b then produces Figure 6c to describe 9-year modulations of QBO and AO. Similar interactions also explain the other features of the spectrum shown in Figure 5, such as the 9-year oscillation interacting with the SAO (54) to produce the harmonics (51, 57). And the symmetric lobes (36, 42) can be tied to 39, which in turn is produced by the QBO interacting with the AO.

In addition to the 9-year modulations, Figure 5 also shows the signatures of modulations involving the symmetric beat period of 4.5 years, which generates for example with the QBO the symmetric harmonics (6, 18) and with the AO the asymmetric harmonics (21, 33).

The above analysis leads to the conclusion that the 4.5 and 9-year beat periods appear primarily in the form of amplitude modulations involving the AO, SAO and QBO. These modulations are significant and extend into the lower stratosphere as seen also from Figures 3 and 4, in contrast to the beat period oscillations themselves which are relatively weak and largely confined to the upper mesosphere.

Considering that the QBO is largely confined to low latitudes and that it generates the above discussed beat oscillation through wave filtering, it is interesting that the effect extends to mid latitudes. With Figure 7 where we present at 40° N the monthly mean zonal winds that clearly reveal the 9- and 4.5-year modulations. Except for the amplitude of the AO, the spectral features are much weaker at this latitude than near the equator as shown in Figure 8. But the lobe harmonics again reveal the above discussed relationship between the beat periods and the QBO, AO and SAO, and the asymmetric 9-year oscillation is seen in the spectrum.

4.2. QBO with 33.5-month Period

Here the GW parameters are chosen to be $k_* = (65 \text{ km})^{-1}$ and $\sigma_{hi} = 3$m/s at 20 km, producing a momentum flux about a factor of 2 larger that in the previous case. The adopted eddy diffusion rate, however, is also almost a factor of 2 larger. In this case, standard solar heating rates were employed to produce zonal winds of about 80 m/s in the winter hemisphere at mid latitudes.

In Figure 9, we present the computed zonal winds at 4° N plotted over a time span of 26 years. At altitudes below 40 km, repeatable features are evident that indicate a modulation with a period of 11 years, but the pattern is not nearly as clean as that shown in Figures 3 and 4. The picture, however, becomes clearer when the spectrum is examined, which is presented in Figure 10 for a time span from 5 to 45 years. This shows a large peak for a period of 10 years. And in this case it represents a symmetric oscillation as indicated in Figure 2, which we interpret to be the product of the QBO interacting with the large SAO that peaks at equatorial latitudes. In this 40-year spectrum, the QBO period peaks at 34.3 months. But it is broadened towards 32 months, and a more detailed analysis indicates that it is around 33.5 months. This QBO period does not strictly obey the beat period relation of Eq. (1), which we take to explain why the beat period of 10 years in Figure 2 falls outside the regular pattern.

Further Examination of the spectrum in Figure 10 indicates that besides the large 10-year peak there is also a related and weaker one around 5 years. The 10-year amplitude modulations of the QBO and SAO appear respectively in the symmetric lobe harmonics (10, 19) and (76, 84), and for the AO in the asymmetric harmonics (37, 44) that extend well below 40 km. Not all the harmonics, however, can be explained and among them 33 and 43 stand out.

The amplitude modulation of the zonal winds are large at 40° N as shown in Figure 11. As is the case at 4° N, the modulation period that initially stands out is close to 11 years, but for the second cycle it is clearly shorter, closer to 9 years. Thus it appears that the periodicity in this case is actually fluctuating to produce, on average, a period of 10 years as shown in the spectrum of Figure 12 for this latitude (and in Figure 10 above). The pronounced spectral features at 40° N can be readily understood. The average beat period of 10 years (4) and its second harmonic of 5 years (8) cause amplitude modulations of the AO (40) that appear respectively in the strong lobes (36, 44) and weaker lobes (32, 48). And similar interactions with the SAO (80) produce the lobes (76, 84) and (72, 88).

As in the case of the earlier discussed 27-months QBO, the beat period around 10 years primarily modulates the amplitudes of the QBO, AO and SAO. Through these modulations, the effect extends down to lower altitudes where the time constants for radiative transfer and eddy diffusion permit long-period oscillations.

Considering that the 10-year oscillation is generated by the QBO, an oscillation confined to low latitudes, it is somewhat surprising that the effect extends with such large magnitude to higher latitudes as shown in Figure 10. In a 2D model, the only avenue to extend the effect must go through the meridional circulation. To capture that, we show in Figure 13 a contour plot of the vertical flow velocity, averaged over a year, which is normalized with a density factor, $\rho^{0.7}$, to reduce the height variations as much as possible. This shows a fairly well defined modulation with a period of about 10 years at altitudes above 30 km. At lower altitudes, it reveals temporal variations associated with the QBO that are perhaps surprising at first sight but are understandable. This is the signature of the meridional circulation driven by the QBO, confined to low latitudes, which produces a feedback that suppresses the oscillation outside the tropics. Allowing for the seasonal variations, we present in Figure 14 the monthly mean of the normalized vertical winds (reduced by a factor of 10 compared with Figure 13). Here again the 10-year modulation is apparent, and we associate that with the corresponding variations in the zonal winds shown in Figure 11.

5. Conclusion

We have demonstrated with a 2D model that the QBO, interacting with the AO and SAO trough GW node filtering, can produce quasi decadal oscillations (QDO) in the stratosphere and mesosphere. To produce a QDO, however, requires that the QBO nearly satisfies the beat period relations for the AO or SAO. The number of periods that qualify is small but they are clustered around 27 months (see Figure 2) where the QBO is observed more frequently.

The QDO signature appears in the form of a stand-alone oscillation largely confined to the upper mesosphere. Its largest signature, however, appears in the amplitude modulations of the QBO, AO and SAO, and these extend also into the lower stratosphere. The downward control that characterizes the QBO apparently comes into play, and the longer time constants for diffusion and radiative loss at lower altitudes facilitate the QDO response.

Although excited by the QBO, which is confined to low latitudes, the QDO is shown to extend to high latitudes. The effect is particularly large for the QBO with period around 33.5 month (near the upper limit of observations), which interacts with the SAO to produce a hemispherically symmetric QDO. Our analysis indicates that the QDO is transferred to high latitudes by the meridional circulation, which prominently exhibits this periodicity particularly in the amplitude modulation of the AO.

References

Baldwin, M. P., and T. J. Dunkerton, Biennial, quasi-biennial, and decadal oscillations of potential vorticity in the northern stratosphere, *J. Geophys. Res.*, **103**, 3919 (1998).

Chan, K. L., H. G. Mayr, J. G. Mengel, and I. Harris, A 'stratified' spectral model for stable and convective atmospheres, *J. Comput. Phys.*, **113**, 165 (1994).

Dunkerton T. J., and M. P. Baldwin, Modes of interannual variability in the stratosphere, *Geophys. Res. Lett.*, **19**, 49 (1992).

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).

Holton, J. R., and H. C. Tan, 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 winter, *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 H. 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. Atmos. Sol. Terr. Phys.*, **54**, 1453 (1992).

Labitzke, K., and H. Van Loon, H., Connection between the troposphere and stratosphere on a decadal scale, *Tellus*, **47A**, 275 (1995).

Mayr, H. G, J. G. Mengel, C. A. Reddy, K. L. Chan, and H. S. Porter, Properties of the QBO and SAO generated by gravity waves, *J. Atmos. Solar Terr. Phys.*, **62**, 1135 (2000).

Mayr, H. G, J. G. Mengel, C. A. Reddy, K. L. Chan, and H. S. Porter, Variability of the equatorial oscillations induced by gravity wave filtering, *Geophys. Res. Lett.*, **25**, 2629 (1998).

Mayr, H. G, J. G. Mengel, C. O. Hines, K. L. Chan, N. F. Arnold, C. A. Reddy, and H. S. Porter, The gravity wave Doppler spread theory applied in a numerical spectral model of the middle atmosphere, 1, Model and global scale variations, *J. Geophys. Res.*, **102**, 26077 (1997).

Naito, Y., and I. Hirota, Interannual variability of the northern winter stratospheric circulation related to the QBO and the solar cycle, *J. Meteorol. Soc. Jpn.*, **75**, 925 (1997).

Van Loon, H., and K. Labitzke, Review of the decadal oscillation in the stratosphere of the northern hemisphere, *J. Geophys. Res.*, **98**, 18919 (1993).

Figure Captions

Figure 1. Schematic, illustrating the process of GW node filtering, which causes an interaction between the QBO and the AO (12 months) or SAO (6 months) to generate beat periods. The GW's propagating up through the nodes of the QBO are least attenuated (i.e., enhanced) and thus carry its imprint. When multiple QBO periods match the opposite phases of the AO or SAO, the enhanced GW's amplify these phases to produce half of the beat period. Long period oscillations are thus generated, and examples are given in the figure.

Figure 2. QBO and beat periods derived for the mechanism illustrated in Figure 1. Plus and square symbols show beat periods generated through interactions with the AO and SAO, respectively. Since the QBO is hemispherically symmetric, its interactions with the asymmetric AO and symmetric SAO produce asymmetric (square) and symmetric (plus) oscillations, respectively. The integer, N, corresponds to the order of QBO periods matching half the beat period as illustrated in Figure 1.

Figure 3. Time series of zonal winds at 4° N and at 20, 40, and 60 km, computed with a QBO of 27 months that generates a 9-year beat period. Note that virtually every feature in the time interval between 5 and 14 years appears again in the subsequent cycle, i.e., 9 years later.

Figure 4. Same as Figure 3 but as time altitude contour plot. Note that the 9-year periodicity extends into the upper mesosphere.

Figure 5. Spectrum of the zonal winds at 4° N delineated into symmetric (top panel) and asymmetric (bottom panel) obtained from a computer solution spanning 27 years, allowing more than 2 years for spin-up. The dominant harmonics at 12, 27, 54 represent respectively the periods (in months, m) of the QBO(27m), AO(12m), SAO(6m). The harmonics (h), 3 and 6, represent respectively the asymmetric 9 year (y) and symmetric 4.5y beat periods (the latter revealing a phase reversal near 70 km that characterizes also the QBO and SAO). The beat periods, however, appear most prominently in the lobe harmonics that describe the amplitude

modulations of the QBO, AO, and SAO. Thus, for example, the 9y modulations of the QBO and AO produce the lobe harmonics (9, 15, asymmetric) and (24, 30, symmetric) respectively as illustrated in Figure 6.

Figure 6. (a) Synthesis of harmonics, h = 9, 12, 15, which describes the 9y modulation of the QBO. (b) Same as (a) but for h = 24, 27, 30 to describe the modulation of the AO. (c) Superposition of (a) and (b) to describe the combined effect.

Figure 7. Same as Figure 4 but for 40° N, which reveals 9y and 4.5y amplitude modulations.

Figure 8. Same as Figure 5 but for 40° N, which shows again the 9y beat period and the corresponding lobe harmonics for the amplitude modulations.

Figure 9. Contour plot of zonal winds at 4° N for a QBO with period of about 33.5m. As shown in Figure 2, this periodicity does not obey as closely the beat relation as the 27m QBO in the previous case. The model results presented nevertheless reveal that this QBO does generate a pronounced quasi decadal oscillation around 10y.

Figure 10. Spectrum from a computer solution for 4° N spanning 40 years, which produced the results shown in Figure 9. In this case the 10y beat period at harmonic 4 is associated with a symmetric oscillation, which implies that it is produced by the QBO interacting with the SAO. The weaker 5y oscillation appears to be the second harmonic arising from non-linear interaction. As in the previous case, lobe harmonics are shown in the spectrum, which describe the amplitude modulations of the QBO at (10, 19), AO at (36, 44) and SAO at (76, 84).

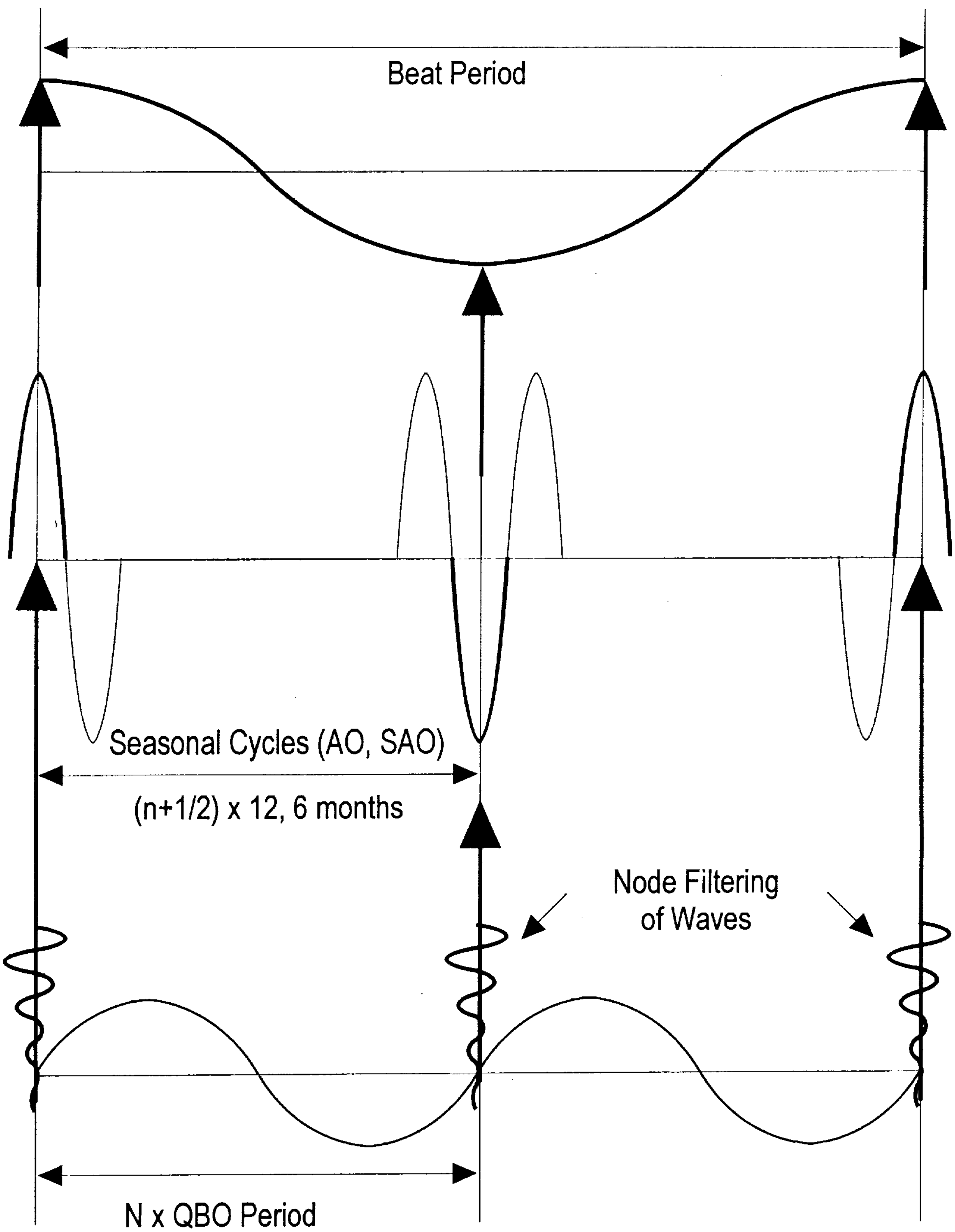
Figure 11. Similar to Figure 9 but for 40° N. Pronounced modulations are shown with a period of 11 years followed by a shorter period of about 9 years.

Figure 12. Same as Figure 10 but for 40° N. In addition to the 10y peak at harmonic 4, the AO and SAO are respectively associated with lobe harmonics (36, 44) and (76, 84), which produce the large amplitude modulations shown in Figure 11.

Figure 13. Contour plot of normalized vertical winds averaged over a year and multiplied with a density factor of $\rho^{0.7}$ to bring out the variations over a larger part of the atmosphere. This shows long term variations with a period around 10 years. Also shown are the signatures of the QBO driven meridional circulation, which produces a feedback that suppresses this oscillation outside the tropics.

Figure 14. Same as Figure 13 but for normalized winds divided by a factor of 10 and averaged over a months. The modulations around 10 year are clearly apparent, revealing phase reversals between 20 and 40 km. These variations are presumably involved in producing the amplitude modulations shown in Figure 11.

Beat Periods Between QBO and Seasonal Cycles Generated by Gravity Wave Node Filtering



QBO (30 months) x AO, N = 1 --> 5-year Beat
QBO (27 months) x AO, N = 2 --> 9-year Beat
QBO (33 months) x AO, N = 2 --> 11-year Beat
QBO (34.5 months) x SAO, N = 2 --> 11.5-year Beat

Figure 1

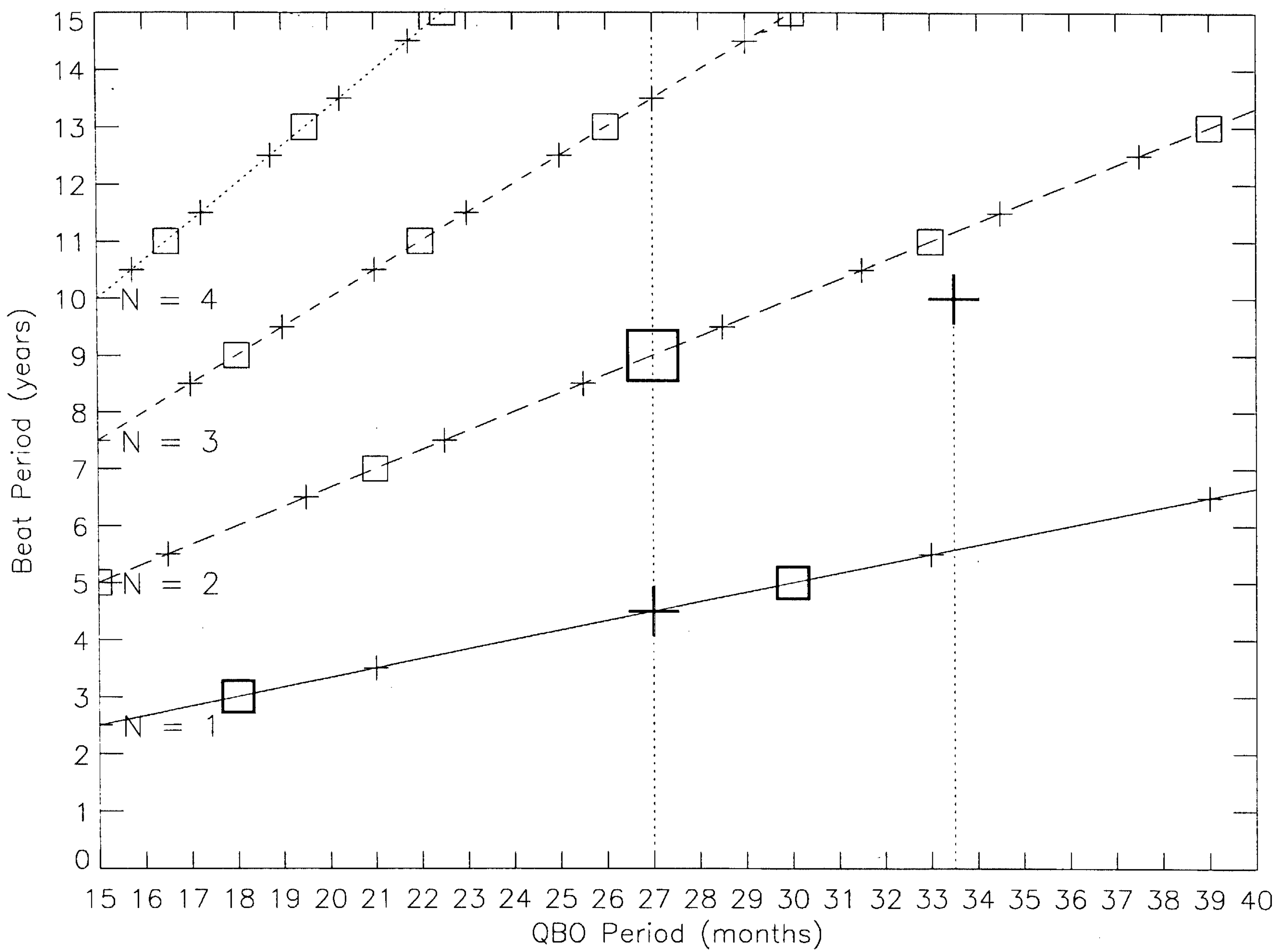
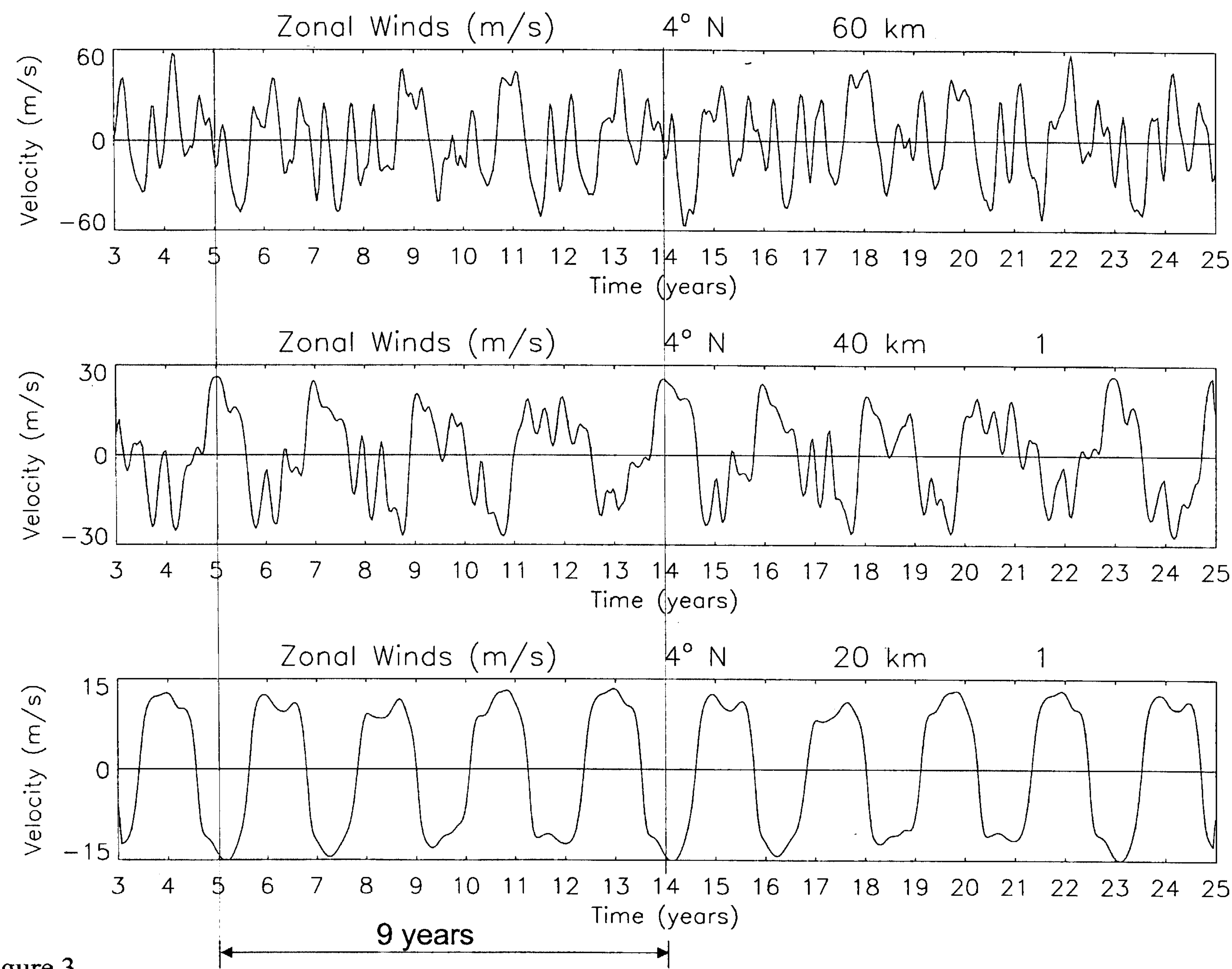


Figure 2



Zonal Winds (m/s) 4° N 60 km
Velocity (m/s)
60
0
−60
3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Time (years)
Zonal Winds (m/s) 4° N 40 km 1
Velocity (m/s)
30
0
−30
3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Time (years)
Zonal Winds (m/s) 4° N 20 km 1
Velocity (m/s)
15
0
−15
3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Time (years)
9 years

Figure 3

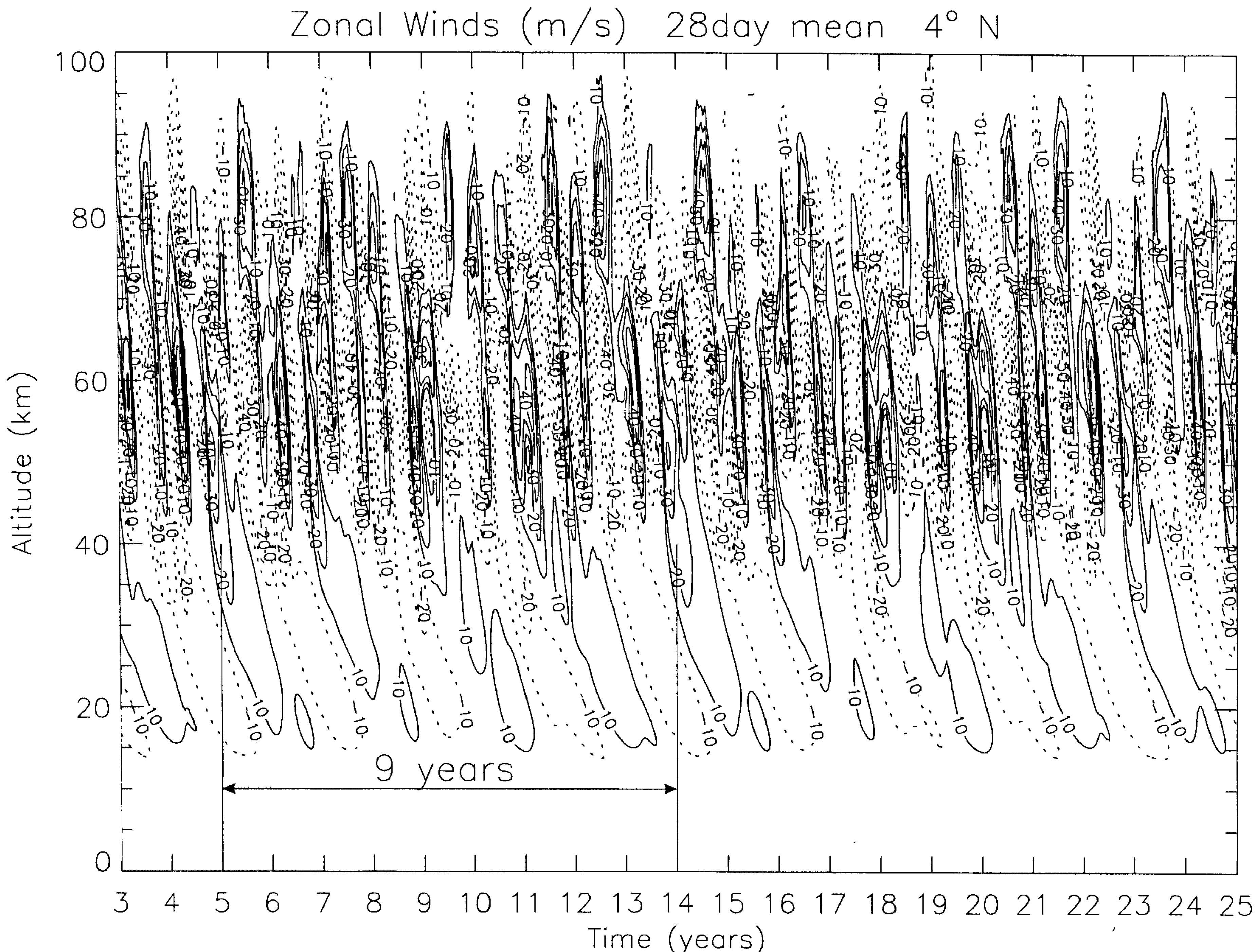
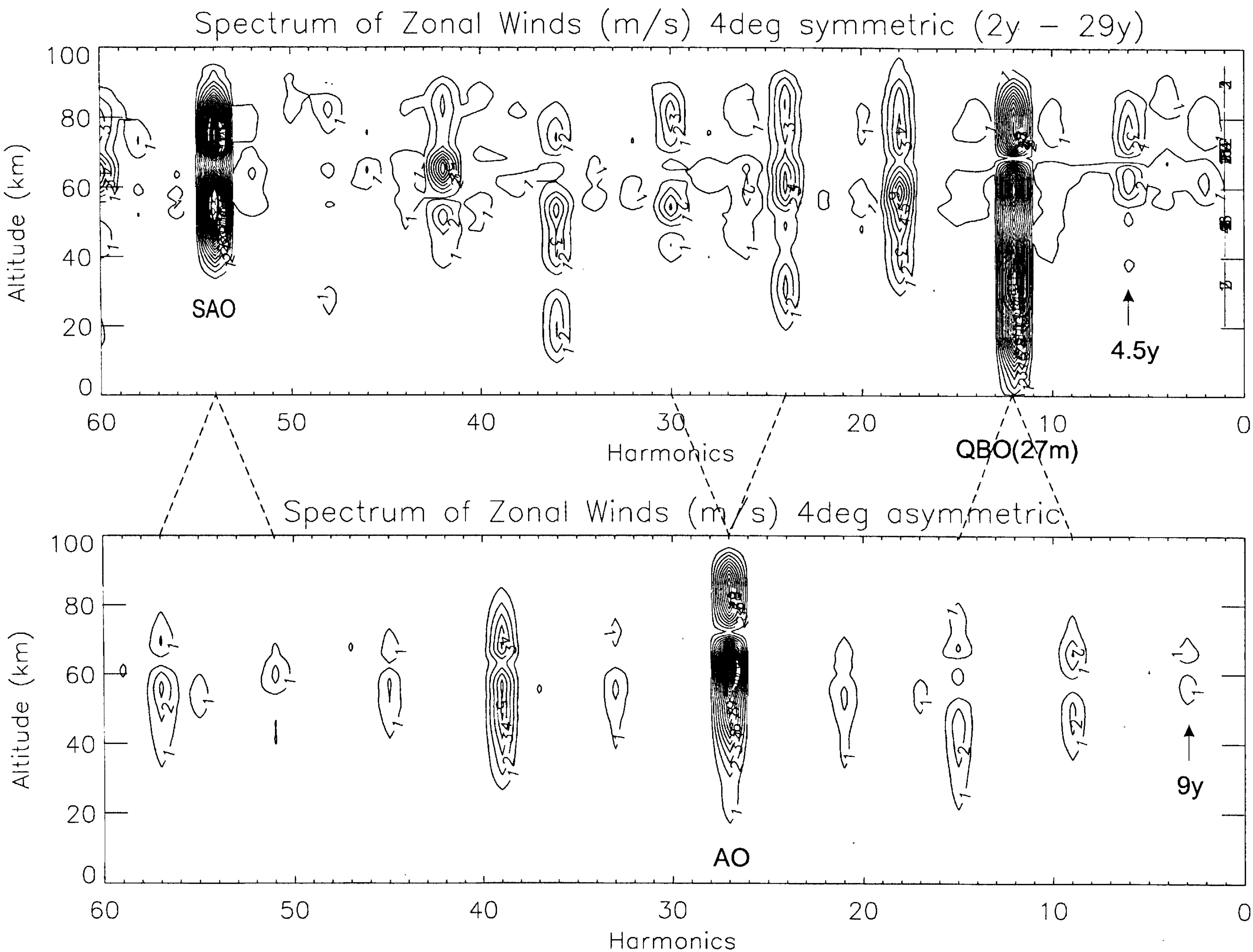


Figure 4



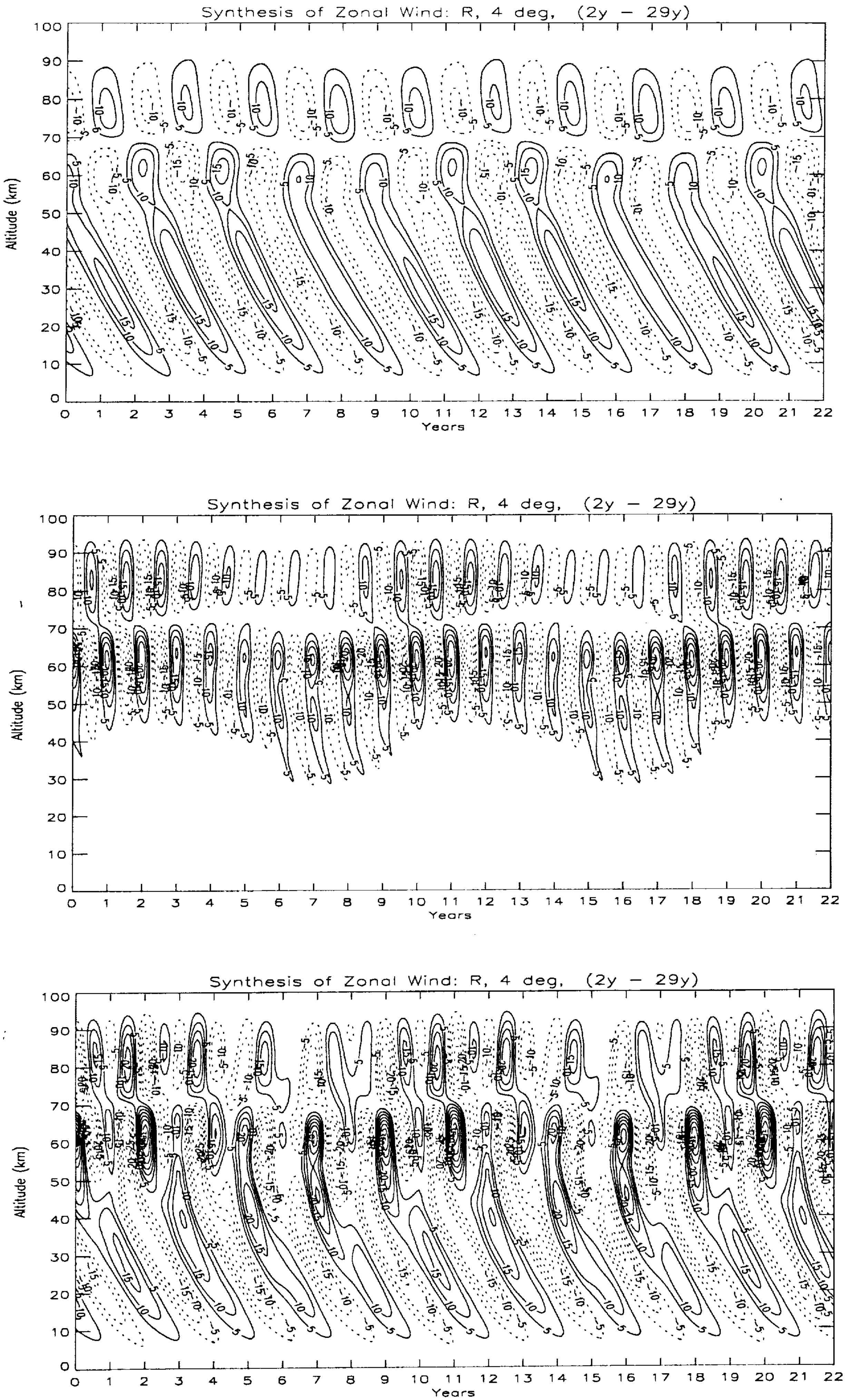
Spectrum of Zonal Winds (m/s) 4deg symmetric (2y − 29y)
Altitude (km)
Harmonics
SAO
QBO(27m)
4.5y
Spectrum of Zonal Winds (m/s) 4deg asymmetric
AO
9y

Figure 5

a

b

c



Synthesis of Zonal Wind: R, 4 deg, (2y – 29y)
Altitude (km)
Years
Synthesis of Zonal Wind: R, 4 deg, (2y – 29y)
Altitude (km)
Years
Synthesis of Zonal Wind: R, 4 deg, (2y – 29y)
Altitude (km)
Years

Figure 6

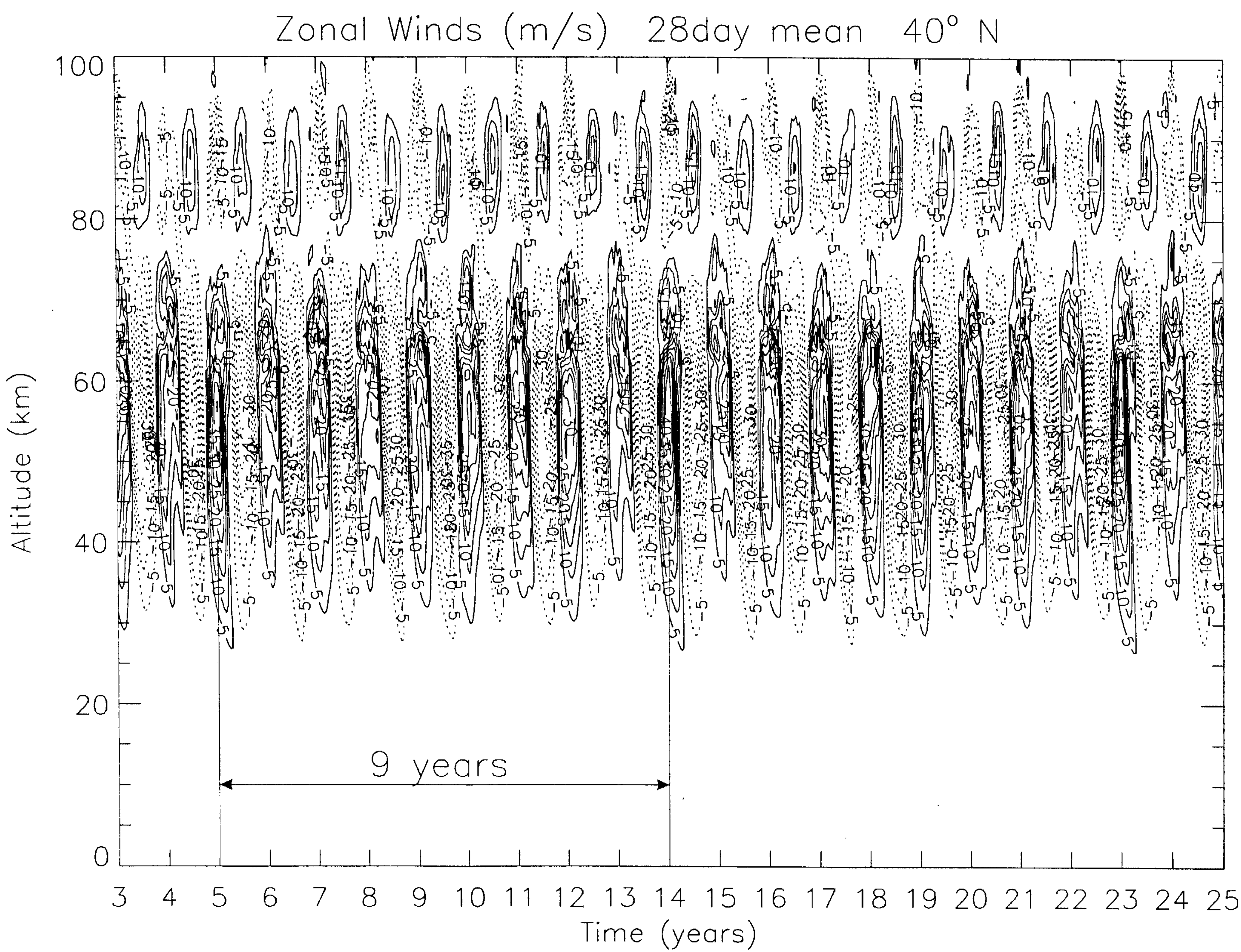


Figure 7

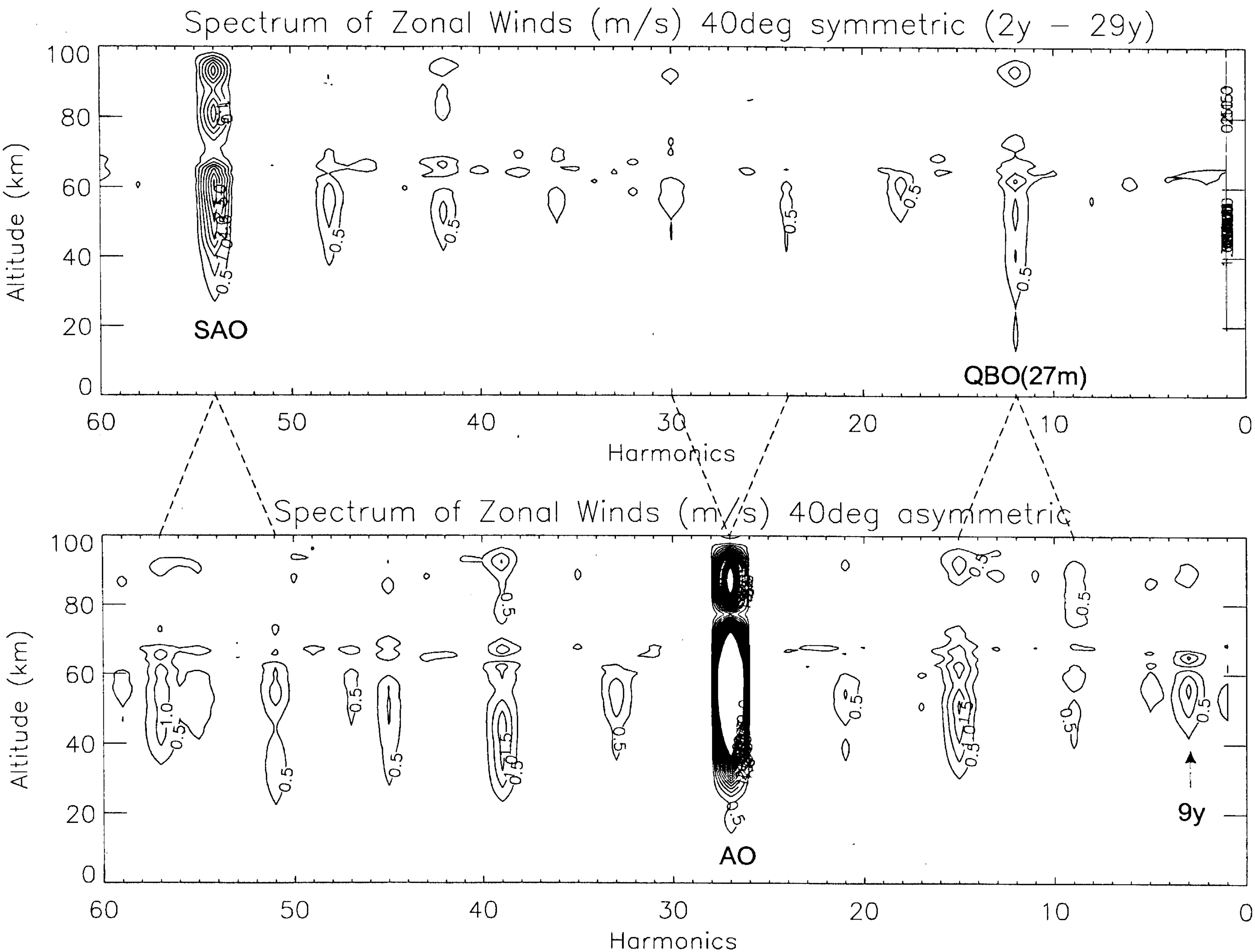

Spectrum of Zonal Winds (m/s) 40deg symmetric (2y – 29y)
Altitude (km)
Harmonics
SAO
QBO(27m)
Spectrum of Zonal Winds (m/s) 40deg asymmetric
AO
9y

Figure 8

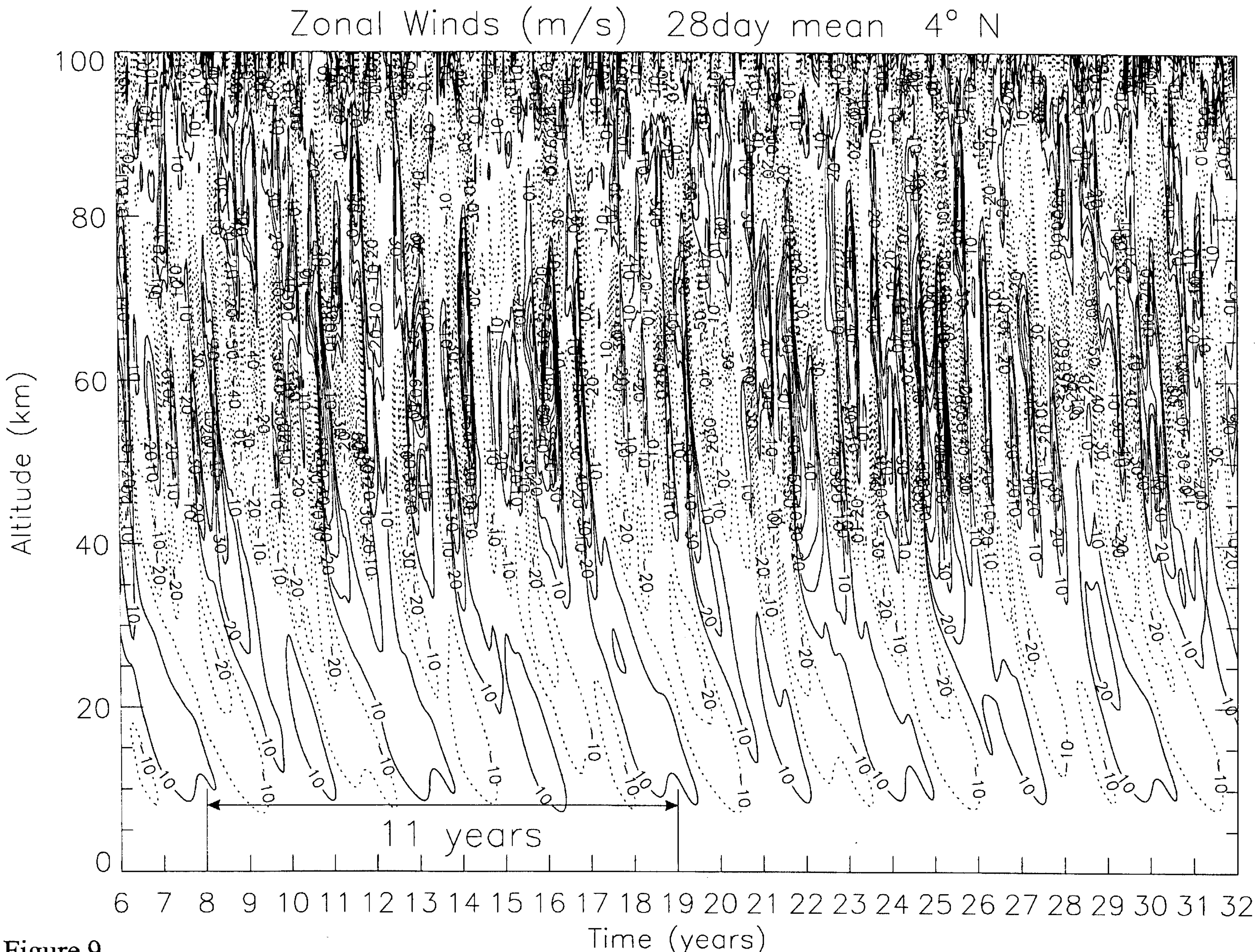


Figure 9

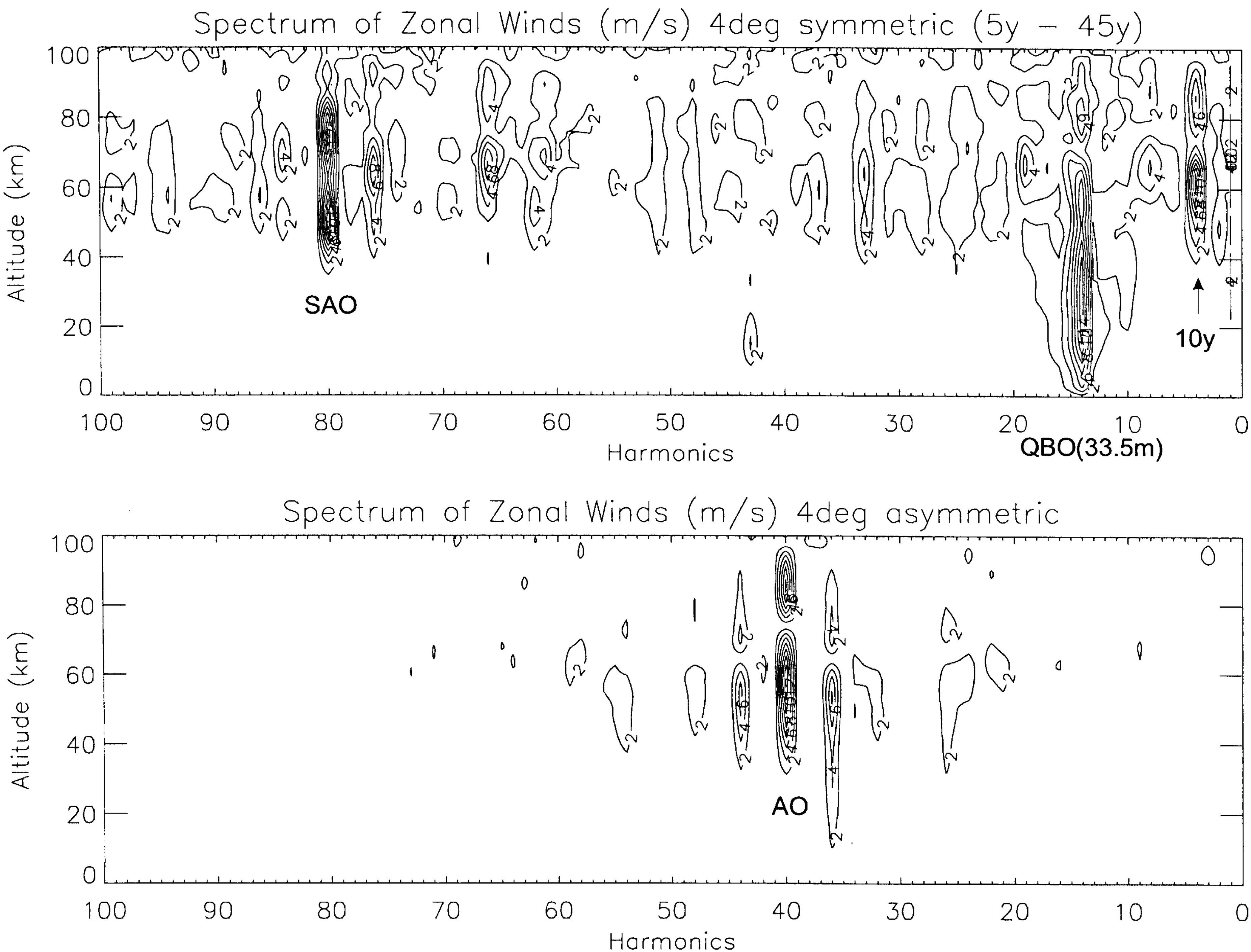
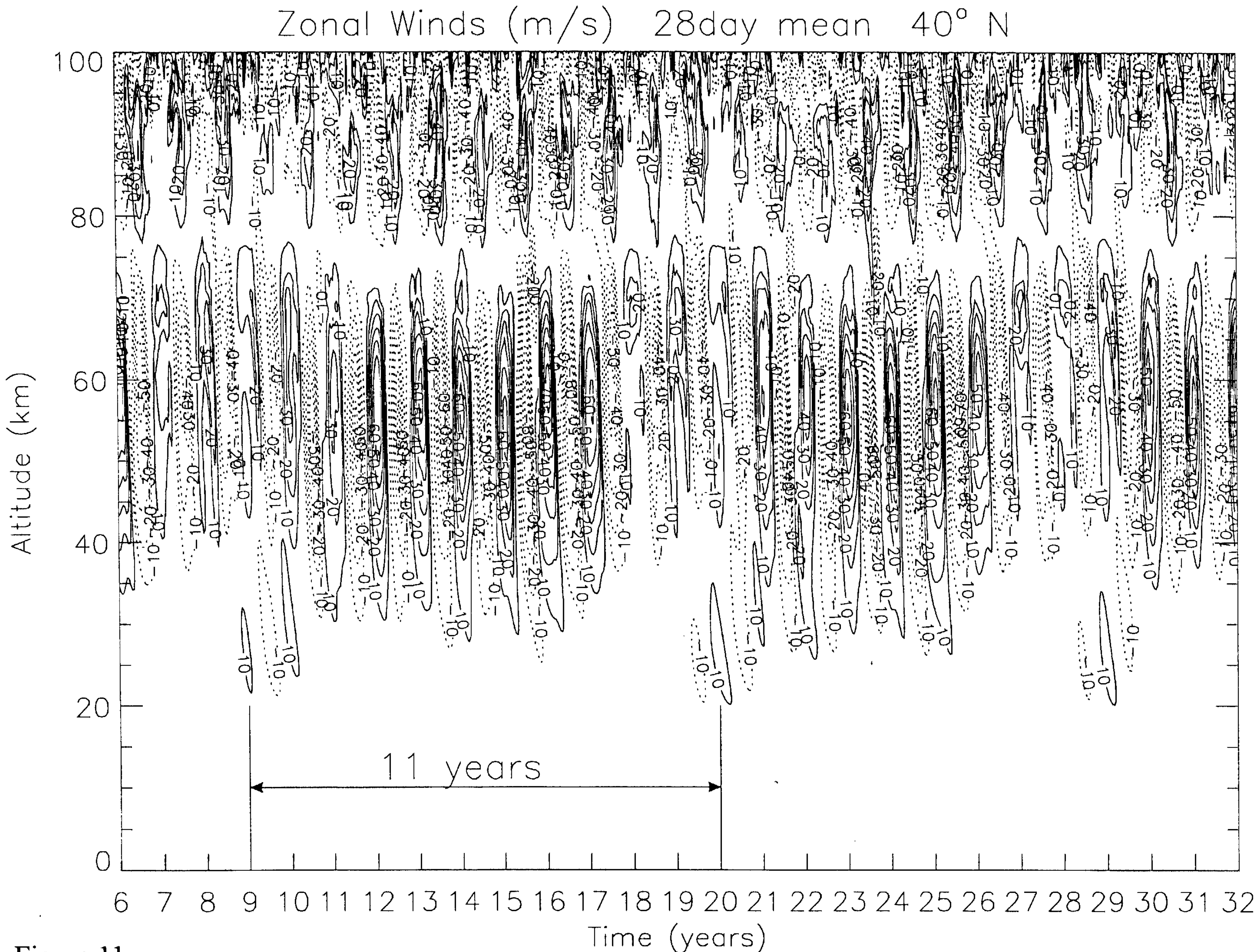

Spectrum of Zonal Winds (m/s) 4deg symmetric (5y – 45y)
Altitude (km)
Harmonics
SAO
QBO(33.5m)
10y
Spectrum of Zonal Winds (m/s) 4deg asymmetric
Altitude (km)
Harmonics
AO

Figure 10



Zonal Winds (m/s) 28day mean 40° N
Altitude (km)
100
80
60
40
20
0
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
Time (years)
11 years

Figure 11

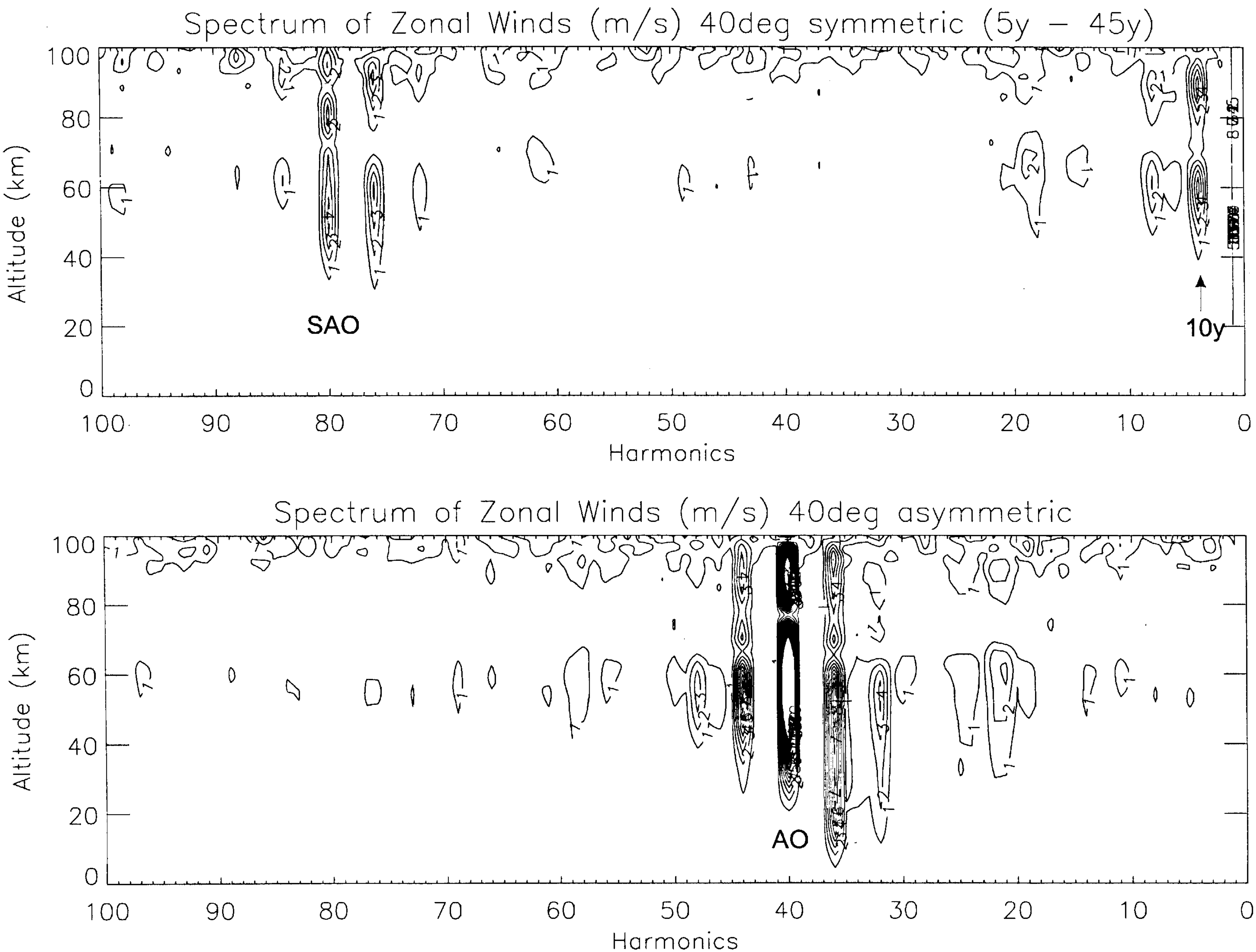

Spectrum of Zonal Winds (m/s) 40deg symmetric (5y – 45y)
Altitude (km)
Harmonics
SAO
10y
Spectrum of Zonal Winds (m/s) 40deg asymmetric
Altitude (km)
Harmonics
AO

Figure 12

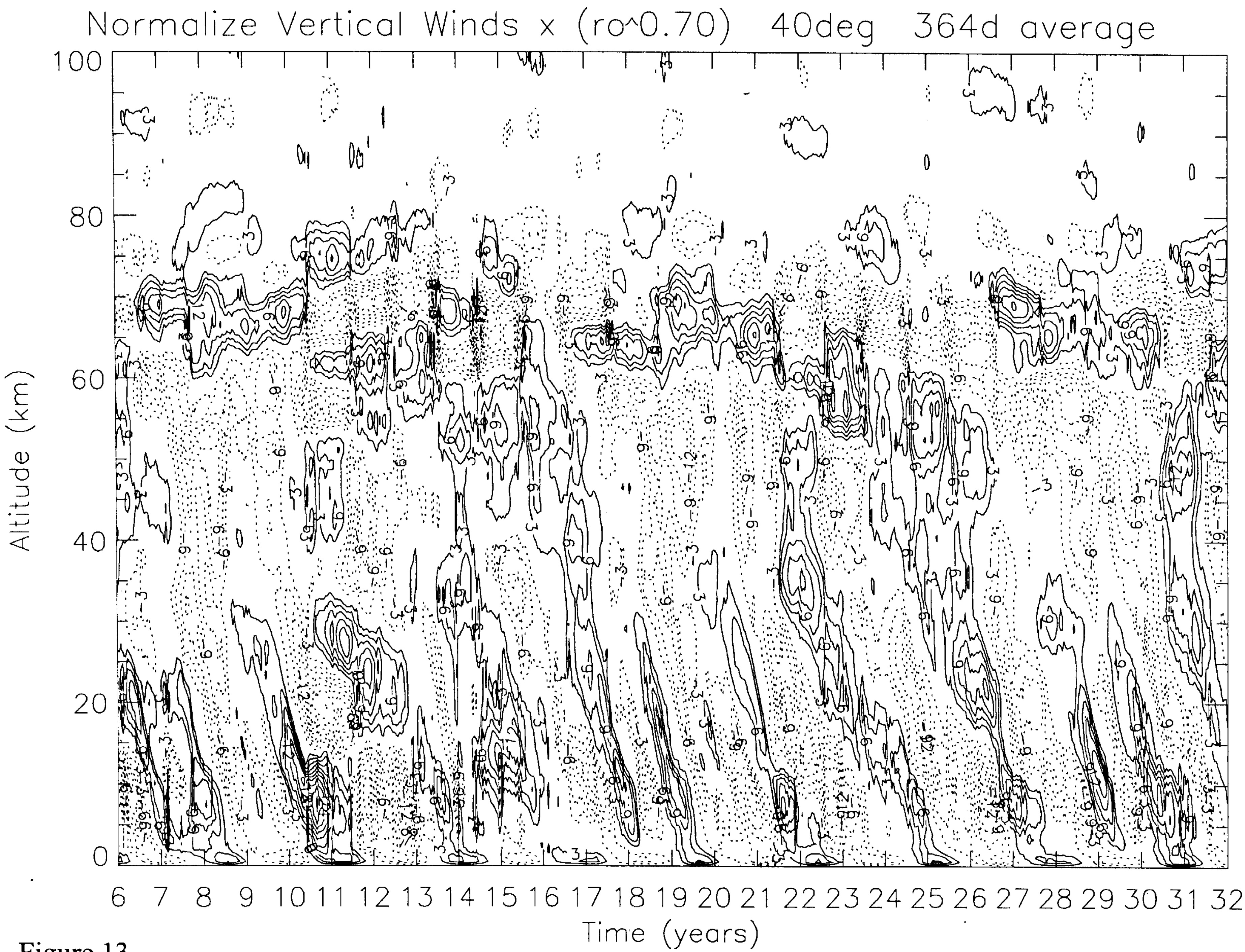

Normalize Vertical Winds x (ro^0.70) 40deg 364d average
Altitude (km)
0
20
40
60
80
100
Time (years)
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32

Figure 13

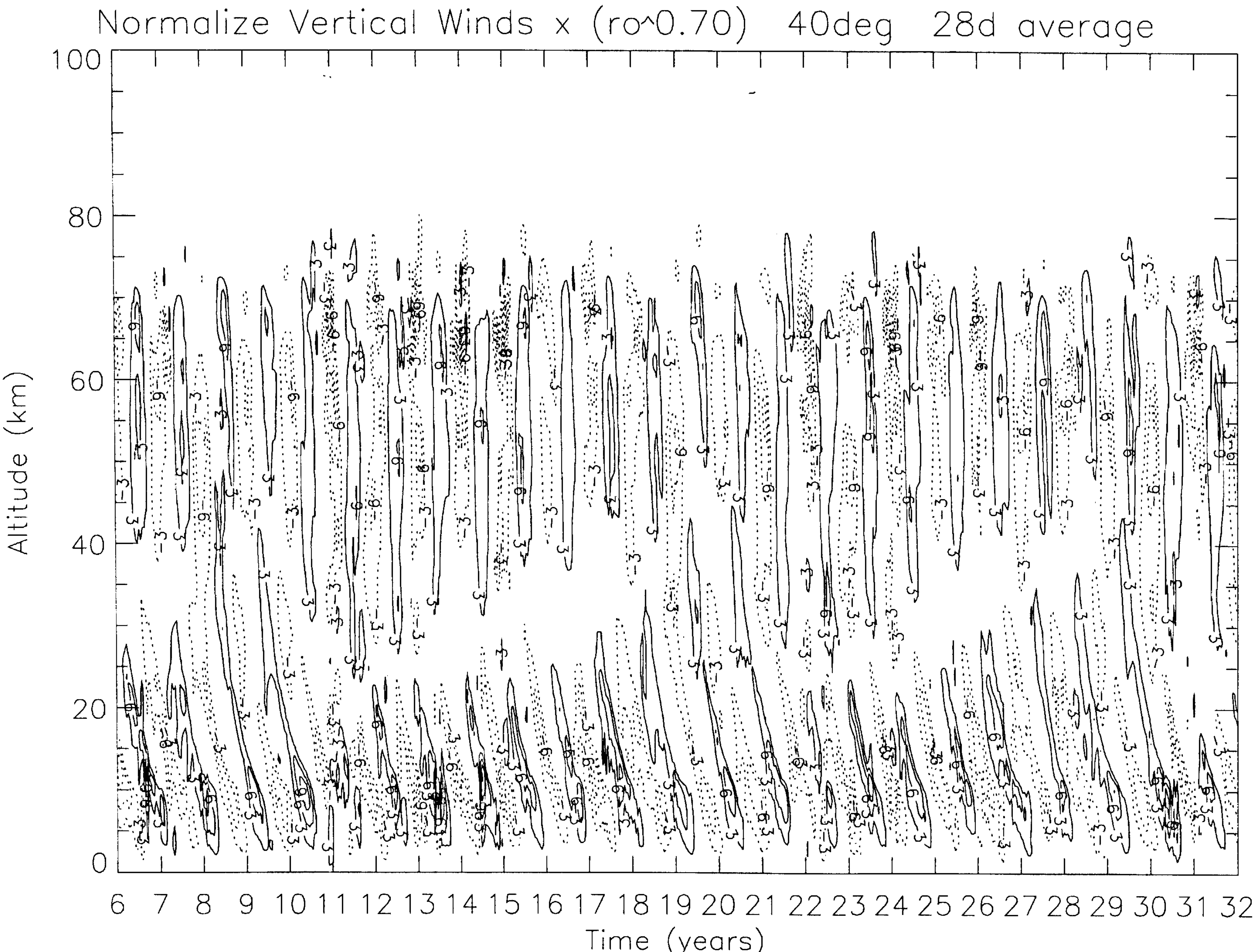

Normalize Vertical Winds x (ro^0.70)   40deg   28d average
Altitude (km)
0
20
40
60
80
100
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
Time (years)

Figure 14

Popular Summary

Quasi-decadal Oscillations Generated by the QBO

H. G. Mayr, J. G. Mengel, D. P. Drob, H. S. Porter, and K. L. Chan

Quasi-decadal oscillations (QDO) have been observed in the stratosphere and have been linked to the equatorial Quasi-Biennial Oscillation (QBO) and to the 11-year solar activity cycle. With the use of a 2D version of our Numerical Spectral Model that incorporates the Doppler Spread Parameterization for gravity waves, we demonstrate that such long-term variations can be generated by the QBO as it interacts through GW filtering with the seasonal variations. Results are discussed from computations covering up to 50 years, and our analyses leads to the following conclusions: Relatively large signatures of the QDO appears in the form of amplitude modulations of the annual and semi-annual variations and these extend into the lower stratosphere. Although excited by the QBO, which is confined to low latitudes, the QDO extend to high latitudes. The QDO is shown to be transferred by the meridional circulation, which prominently exhibits this periodicity particularly in the amplitude modulation of the annual variations.