The QBO as Potential Amplifier and Conduit to Lower Altitudes of Solar Cycle Influence

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Abstract: The solar cycle (SC) effect in the lower atmosphere has been linked observationally to the Quasi-biennial Oscillation (QBO), which is generated primarily by small-scale gravity waves. Salby and Callaghan (2000) analyzed the QBO observations covering more than 40 years and found that it contains a relatively large SC signature at 20 km. Following up on a 2D study with our Numerical Spectral Model (NSM), we discuss here a 3D study in which we simulated the QBO under the influence of the SC. For a SC period of 10 years, the amplitude of the relative variations of radiative forcing is taken to vary from 0.2% at the surface to 2% at 50 km to 20% at 100 km and above. This model produces in the lower stratosphere a relatively large modulation of the QBO, which appears to be related to the SC and is in qualitative agreement with the observations. Further studies are needed, (1) to determine whether the effect is real and the results are robust and (2) to explore the mechanism(s) that may amplify the SC effect. Quasi-decadal oscillations, generated internally by the QBO interacting with the seasonal cycles, may interfere with or aid the SC effect.

I. Introduction

In the lower atmosphere, the variations in the solar radiation are too small to account for the observed solar cycle (SC) effects. Dynamical effects are thus likely to come into play -- and the wave driven Quasi-biennial Oscillation (QBO) has been invoked as a potential leverage.

Following a study by Holton and Tan (1980) that revealed an influence of the phase of the 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 is in its negative and positive phase respectively. And at mid-latitudes they observed opposite correlations. 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 correlated with the QBO and SC. From the above observations it appears that the QBO may acts a catalyst to bring about the SC connection. But there are also observations, which indicate that the QBO itself is directly affected by the SC.

Salby and Callaghan (2000) spectrally analyzed the 40-year record of the measured zonal winds in the equatorial QBO at an altitude of about 20 km. The resulting power spectrum in their Figure 1 shows a large and sharp peak at 0.41 cycles per year (cpy), corresponding to a QBO period of about 29 months. In addition to that peak, the spectrum also reveals smaller but distinct neighboring maxima at 0.5 and 0.59 cpy. The difference frequency 0.5 – 0.41 = 0.09 cpy corresponds to about 11 year^{-1}, and it was interpreted to be the signature of the 11-year SC modulation of the QBO. The second feature in the spectrum 0.59 - 0.41 = 0.18 cpy was interpreted to be the signature of the QBO interacting with the annual cycle, but it could also be second harmonic of the 11-year cycle since it corresponds to a period of 5.5 years. To isolate the solar cycle signature, Salby and Callaghan proceeded to synthesize or band-pass filter the QBO with its spectral side-lobes. The synthetic solar cycle modulation of the QBO over more than

40 year then showed the zonal wind power to vary at 20 km from about 150 to about 400, which corresponds to a relatively large variation in the winds from about 12 to 20 m/s.

These observations have been the impetus for the 3D modeling study discussed here in which we make an attempt to simulate the SC modulation of the QBO.

II. The Quasi-biennial Oscillation (QBO) and "Downward Control"

The QBO (with periods between 22 and 34 months), and recently reviewed by Baldwin et al. (2001), is confined to low latitudes where it dominates the zonal circulation of the lower stratosphere (Reed, 1965, 1966), but it is also observed in the upper mesosphere (Burrage et al., 1996). Closely connected with the QBO is the Semi-Annual Oscillation (SAO), which dominates the equatorial circulation of the upper stratosphere and mesosphere (Hirota, 1980). It was demonstrated by Lindzen and Holton (1968), Holton and Lindzen (1972) and others (e.g., Plumb, 1977, 1984; Dunkerton, 1985) for the QBO, and by Dunkerton (1979) and Hamilton (1986) for the SAO, that these stratospheric oscillations can be driven by the momentum deposition of upward propagating planetary waves. More recently, however, modeling studies with observed planetary waves have lead to the conclusion that small-scale gravity waves (GW) are more important (e.g., Hitchman and Leovy, 1988; Takahashi and Boville, 1992; Hamilton et al., 1995). Applying the Doppler Spread Parameterization (DSP) of Hines (1997a, b), we were among the first to reproduce in our model the QBO (and SAO) extending from the lower stratosphere into the upper mesosphere (e.g., Mengel et al., 1995; Mayr et al., 1997).

In principle, the QBO can be understood as a wave-driven non-linear auto-oscillator, which, like the mechanical clock, does not require any external time dependent forcing to maintain the oscillation. In the context of the phenomenon discussed here, however, it is important to emphasize that the QBO and its period in particular are strongly influenced by external variations. In the seminal theory for the QBO by Lindzen and Holton (1968), the seasonal cycle and resulting SAO at higher altitudes were invoked to seed the QBO extending down into the lower stratosphere. Holton and Lindzen (1972) subsequently concluded, however, that the seasonal cycle was not essential to generate the oscillation. This was confirmed with 2D computer experiments (Mayr et al., 1998, see Figure 6), where QBO like oscillations were generated (a) for perpetual equinox and (b) with the regular seasonal cycle of solar heating. The imposed seasonal cycle increased the period of the QBO from about 17 to 21 months and caused its amplitude to increase by more than a factor of two in the lower stratosphere.

Owing to this generation mechanism of the QBO, being mainly driven by waves but strongly influenced by solar heating, the QBO thus could be influenced also by the SC whose signature then is transferred to lower altitudes. Two factors are important for this mechanism: First, waves can efficiently generate the QBO at equatorial latitudes because, with the Coriolis force vanishing there, the meridional circulation is not involved to redistribute the flow momentum. The flow is essentially trapped near the equator, and the wave interaction combined with diffusion cause the QBO to propagate down to lower altitudes, which is referred to as "downward control". Second, the time constant for eddy diffusion in the lower stratosphere is on the order of years, and this would be conducive for generating the SC variations at lower altitudes.

In a recent paper Mayr et al. (2003b), we conducted two studies to explore the above-discussed dynamical mechanism that may conspire to enhance the SC effect through the QBO. In each case our 2D model was run with and without the SC, and we looked at the resulting differences in the zonal wind fields. In the first case study, the QBO had a period of 30 months, which is exceptionally stable because it is synchronized by and phase-locked to the annual oscillation of solar heating. The SC then could only modulate the amplitude of the QBO, and the effect was relatively small. In the second case, the QBO period, around 33 months, was highly 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, and this produced much larger differences in the computed wind velocities.

III. 3D Modeling Study with QBO and Solar Cycle Effect

The above-discussed modeling study was only conducted in 2D. Moreover the results of this study cannot be tested with observations since nature does not give us the luxury to produce the QBO with and without the SC influence. Thus we carried out a more realistic 3D study with our NSM in which we explicitly isolate the SC modulation of the QBO for comparison with the observations by Salby and Callaghan (2000). With a 10-year solar cycle, the imposed height profile of the variable solar forcing is similar to that employed earlier (Mayr et al., 2003b). Growing exponentially with height, the adopted amplitude of the relative variation in solar radiation is taken to be 0.2 % at the surface, 2 % at 50 km and 20 % at 100 km and above as illustrated with Figure 1.

III.1 Numerical Spectral Model (NSM)

The Numerical Spectral Model (NSM) was introduced by Chan et al. (1994), and 2D as well as 3D applications were used 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., 1994; Mayr et al., 1997, 2003a, b; Mayr and Mengel, 2005). For the zonal mean (wavenumber m = 0), the NSM is driven by the absorption of EUV and UV radiation, with the heating rates for the mesosphere and stratosphere taken from Strobel (1978). The radiative loss is described in terms of Newtonian cooling. We adopted the cooling parameterization developed by Zhu (1989) and modified that at altitudes below 20 km to match the more realistic rates obtained from radiative codes as discussed by Dunkerton (1997). For the solar driven thermal 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 small-scale gravity waves that was formulated by Hines (1997a, b). The DSP deals with a spectrum of waves that interact with each other to produce Doppler spreading, which in turn affects the interactions of the waves with the background flow. To account for the enhanced wave activity associated with convection in the tropics, a latitude dependent tropospheric GW source is adopted that peaks at the equator. For simplicity, the source is taken to be isotropic and independent of season.

To resolve the GW interactions with the flow, the model is run with a vertical integration step of 0.5 km below 120 km altitude. In the horizontal, however, the model is truncated at the maximum meridional and zonal wavenumbers that are respectively l = 12 (12 Gaussian point per hemisphere) and m = 4. The 3D version of the NSM discussed here incorporates tropospheric heating for the zonal mean to reproduce qualitatively the observed zonal jets and temperature variations near the tropopause.

III.2 3D Model Results

With the initial conditions set to zero, the NSM was run with and without the SC covering a limited time span of only 40 years or 4 solar cycles. The results therefore must be considered preliminary. As shown in Figure 2 for the computed zonal winds near the equator, the QBO in this model is fairly realistic. With a period close to 24 months, the winds are about 20 m/s at 30 km, and at higher altitudes the wave-driven semi-annual oscillations (SAO) have amplitudes exceeding 30 m/s.

Allowing enough time for spin-up, the first 10 years of simulation are ignored, and the remaining 30 model years are spectrally analyzed to reveal the SC signature. In Figure 3 we present then the spectra from the solutions obtained with SC (a) and without (b) for comparison. In both cases, the spectral feature of the QBO is well defined. With harmonic, h = 16, for the 30 year time span analyzed, the oscillation period for the QBO is 22.5 months. Given the relatively short time span for this numerical experiment, the spectral features that would define the SC signature in Figure 3 are not pronounced. However, a side lobe for the 10-year modulation does appear at h = 16 - 3. Moreover, there is an indication that the next harmonic is also present as seen in the weak spectral features around h =16 ± 6 that represent the 5-year component.

To reveal the corresponding modulations of the QBO, we present in Figure 4 a synthesis or band-pass filter of the relevant spectral features h = 16 and 16 ± 3. With the SC (a), the magnitude of the computed modulation is relatively large causing the QBO amplitude to vary from about 12 to 21 m/s at 30 km. By comparison, the corresponding QBO modulation is negligible for the solution without the SC (b).

In the analysis discussed here, an important factor is the QBO response in relation to the phase of the imposed SC forcing, which is presented in Figure 4 with dashed lines. From this it is apparent that the peak of the QBO (a) occurs close to the SC maximum, but it does not follow but precede the maximum. This pattern differs from that seen in the modeled circulation away from the equator, which peaks slightly after the SC maximum but is also controlled more directly by the absorbed solar radiation. Considering that the wave driven QBO is a complex dynamical phenomenon, we cannot readily explain this phase difference. But we note that in the solution without SC (b) the much weaker QBO modulation also peaks before the maximum in the solar input. As later discussed, Quasi-decadal Oscillation (QDO) can also be generated internally, and they may interfere with or aid the SC effect.

The above discussion concentrated on the region around the equator where the QBO is generated. But the signatures of the QBO also extend to high latitudes. This is shown with Figure 5 where we present the spectrum (a) and synthesis (b) of the computed temperature perturbations near the pole. Although the SC modulations of the QBO are small, about 1K, they appear in the troposphere below 10 km. It is not understood how this effect is generated in the model and in particular why it occurs at such low altitudes. The meridional circulation could produce the effect in principle, but planetary waves are also likely involved.

V. Summary and Future Course

In a number of papers going back more than 20 years, the QBO has been linked to the SC. Some of these report correlations linking the SC with the observed temperature variations at high latitudes and the phase of the QBO. The impetus for the modeling study presented here has been the paper by Salby and Callaghan (2000), which shows that the QBO itself appears to exhibit a relatively large SC signature in the lower stratosphere.

Based partially on studies with a 2D version of our Numerical Spectral Model (NSM), we envision that the variable solar forcing at higher altitudes (say 50 km) can change the phase and period of the QBO, which is generated mainly by wave-mean flow interactions. The somewhat vague concept of "downward control" has been invoked to describe the seeding of the QBO by the seasonal cycle (Lindzen and Holton, 1968), and it is invoked for the SC in the present context. To affect such a modification presumably would not require much energy, but could have significant consequences for the QBO that extends all the way down into the lower stratosphere and upper troposphere.

Testing the above hypothesis, we carried out a 3D study in which we simulated with our NSM the SC influence on the QBO. The results, presented in Figures 2 through 5, indicate that we can reproduce some aspects of the observed large variations in the zonal winds of the lower stratosphere near the equator reported by Salby and Callaghan (2000). And associated with that, a significant SC signature is generated in the tropospheric temperature of the polar region. While our modeling study thus produced results that are intriguing and potentially promising, our findings must be considered preliminary. A great deal of work still needs to be done to make sure the SC signatures in the model are robust and that we understand them.

One potential problem with Quasi-Decadal Oscillations (QDO) is that such variations could also be generated internally by the QBO as it interacts through GW filtering with the annual oscillation (AO) or semi-annual oscillation (SAO), as was demonstrated with a 2D modeling study (Mayr et al., 2002a). Depending on the period of the QBO, beat periods between 9 and 11 years can be generated that appear in the amplitude modulations of the QBO, AO and SAO, extending 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 again facilitate the QDO response. Such variations could interfere with, or aid, the above-described SC influence.

Having demonstrated with our 3D model that the QBO could potentially serve as a conduit to transfer the SC effect to lower altitudes, and thereby amplify it, we need to further examine these findings before we can accept them. This will require (a) that the model is run over many solar cycles to assure the SC signature persists, (b) that we perform parametric studies with different altitude and time integration steps to make sure the results are robust, (c) that the model is run to simulate more closely the observed QBO periods around 28 months, and (d) that we perform numerical experiments, with artificial SC forcing perhaps, to explore the mechanism(s) that are involved in amplifying the SC influence through the QBO, if confirmed.

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Figure Captions

Figure 1: Schematic, illustrating the adopted height variation of the relative solar cycle (SC) variations in the heating rate on a logarithmic scale.

Figure 2: Computed zonal winds near the equator show the Quasi-biennial Oscillation (QBO) with a period close to 24 months and 20 m/s amplitude at 30 km. Higher up, the Semi-annual Oscillation (SAO) dominates with zonal wind amplitudes exceeding 30 m/s.

Figure 3: Spectra in terms of harmonics for a time span from 10 to 40 years computed from solutions with(a) and without (b) the 10-year SC. Identified are the QBO signatures at h = 16, and in (a) the weak side lobes for the 10-year SC at h =-13 (16 - 3) and its 2nd (5-year) harmonic at h = 22 (16 + 6).

Figure 4: A synthesis or band pass filter is presented for the harmonics h = 16 with 13 and 19 (16 ± 3). In (a), with SC forcing, the QBO amplitude varies at 30 km from about 12 to 21 m/s, which is in qualitative agreement with the observations by Salby and Callaghan (2000). Without SC (b), the corresponding amplitude modulation is negligible. For comparison, the phase of the SC is presented with dashed lines, and it shows in (a) that the QBO precedes not follows the SC maximum, which is not understood.

Figure 5: Computed spectrum (a) for the temperature variations in the polar region reveals the QBO and SC signatures at altitudes around 10 km. The synthesis of the spectral features h = 16 with h = 13, 19 (16 ± 3) is shown in (b) to indicate a weak (< 1K) modulation of the QBO.

Relative Variation of Solar Input

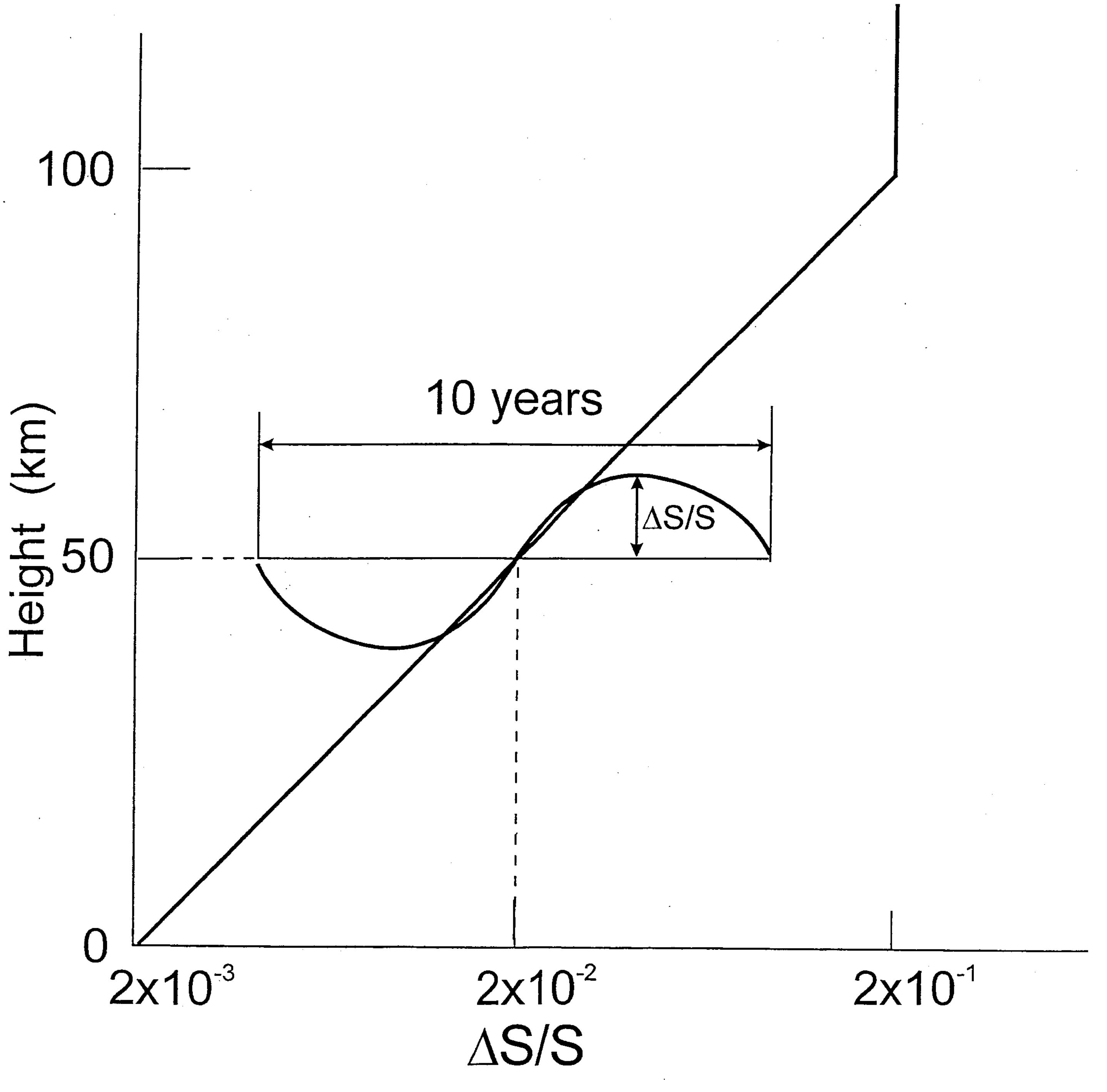


Figure 1

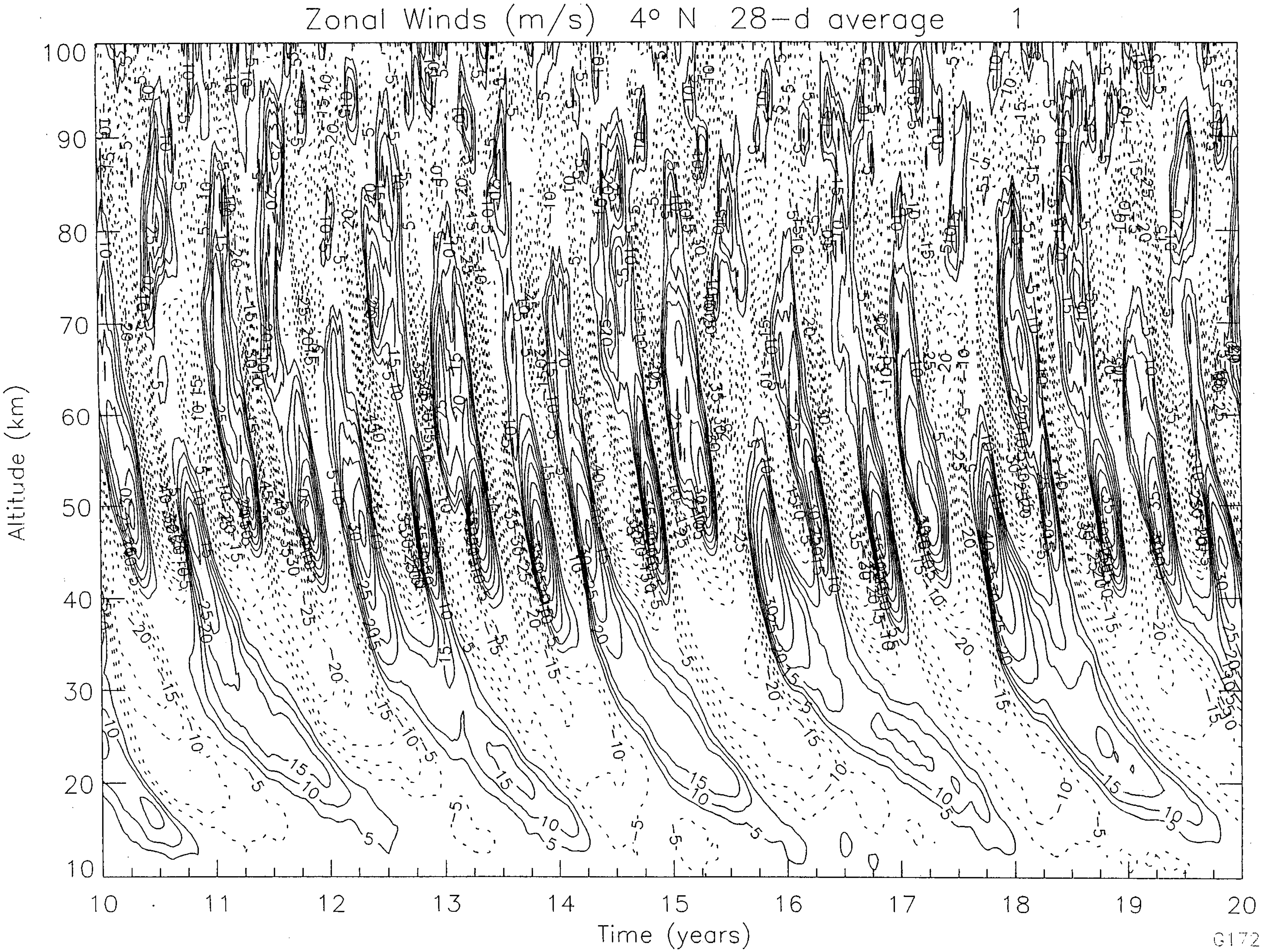
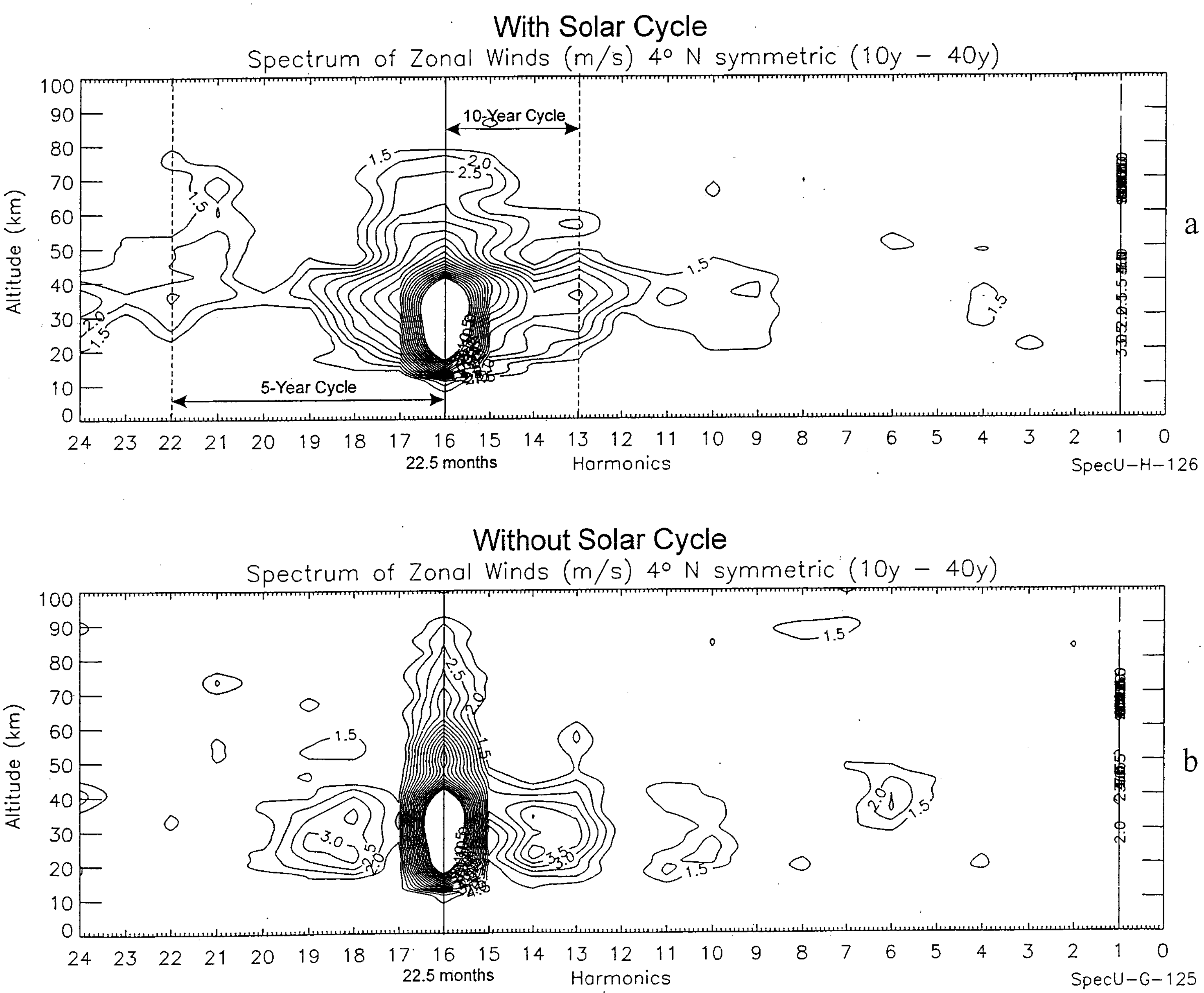


Figure 2


With Solar Cycle
Spectrum of Zonal Winds (m/s) 4° N symmetric (10y – 40y)
Altitude (km)
10-Year Cycle
5-Year Cycle
1.5
2.0
2.5
22.5 months
Harmonics
SpecU–H–126
a
Without Solar Cycle
Spectrum of Zonal Winds (m/s) 4° N symmetric (10y – 40y)
Altitude (km)
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2.0
2.5
3.0
3.5
22.5 months
Harmonics
SpecU–G–125
b

Figure 3

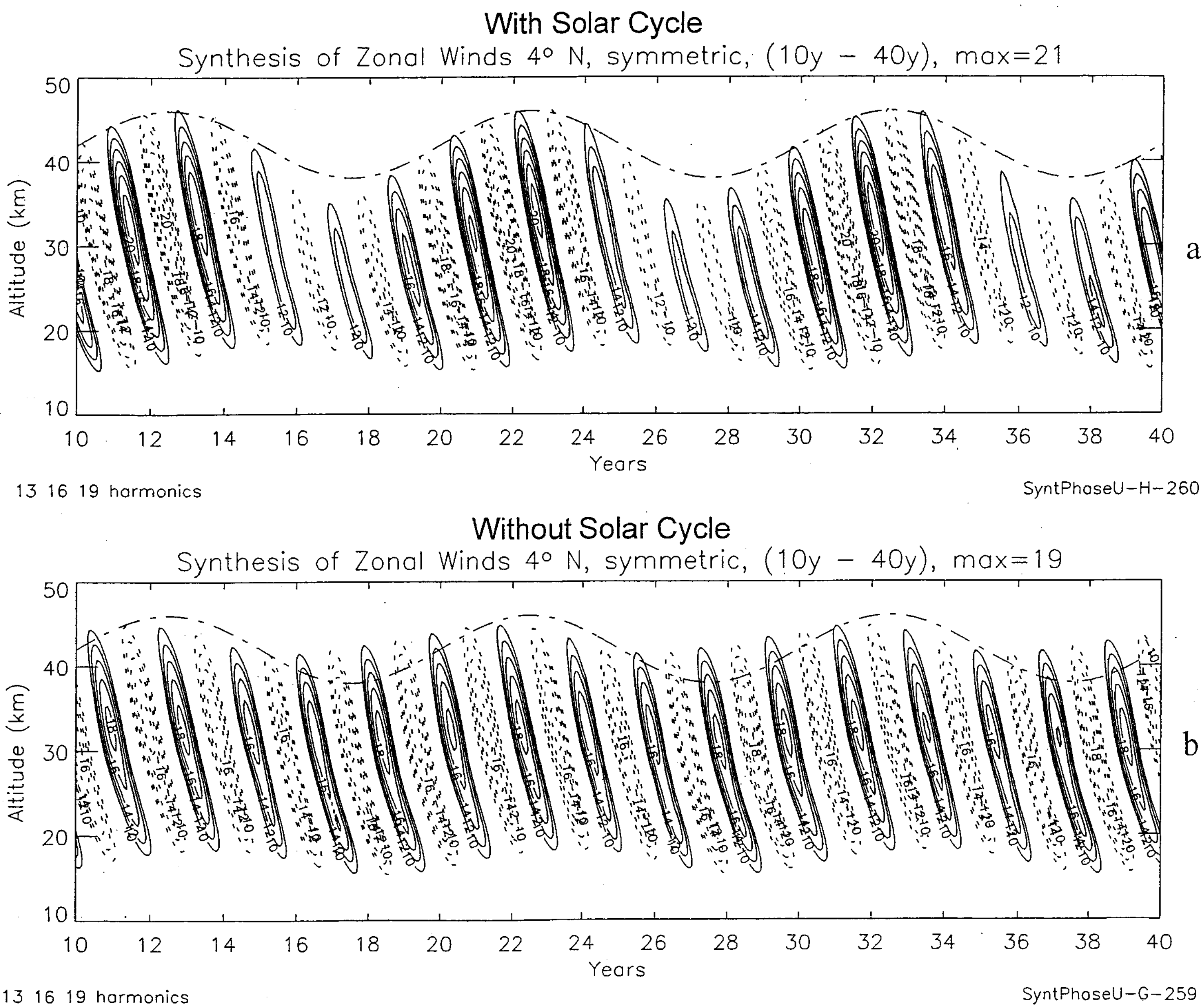
With Solar Cycle
Synthesis of Zonal Winds 4° N, symmetric, (10y – 40y), max=21
Altitude (km)
Years
13 16 19 harmonics
SyntPhaseU-H-260
a
Without Solar Cycle
Synthesis of Zonal Winds 4° N, symmetric, (10y – 40y), max=19
Altitude (km)
Years
13 16 19 harmonics
SyntPhaseU-G-259
b

Figure 4

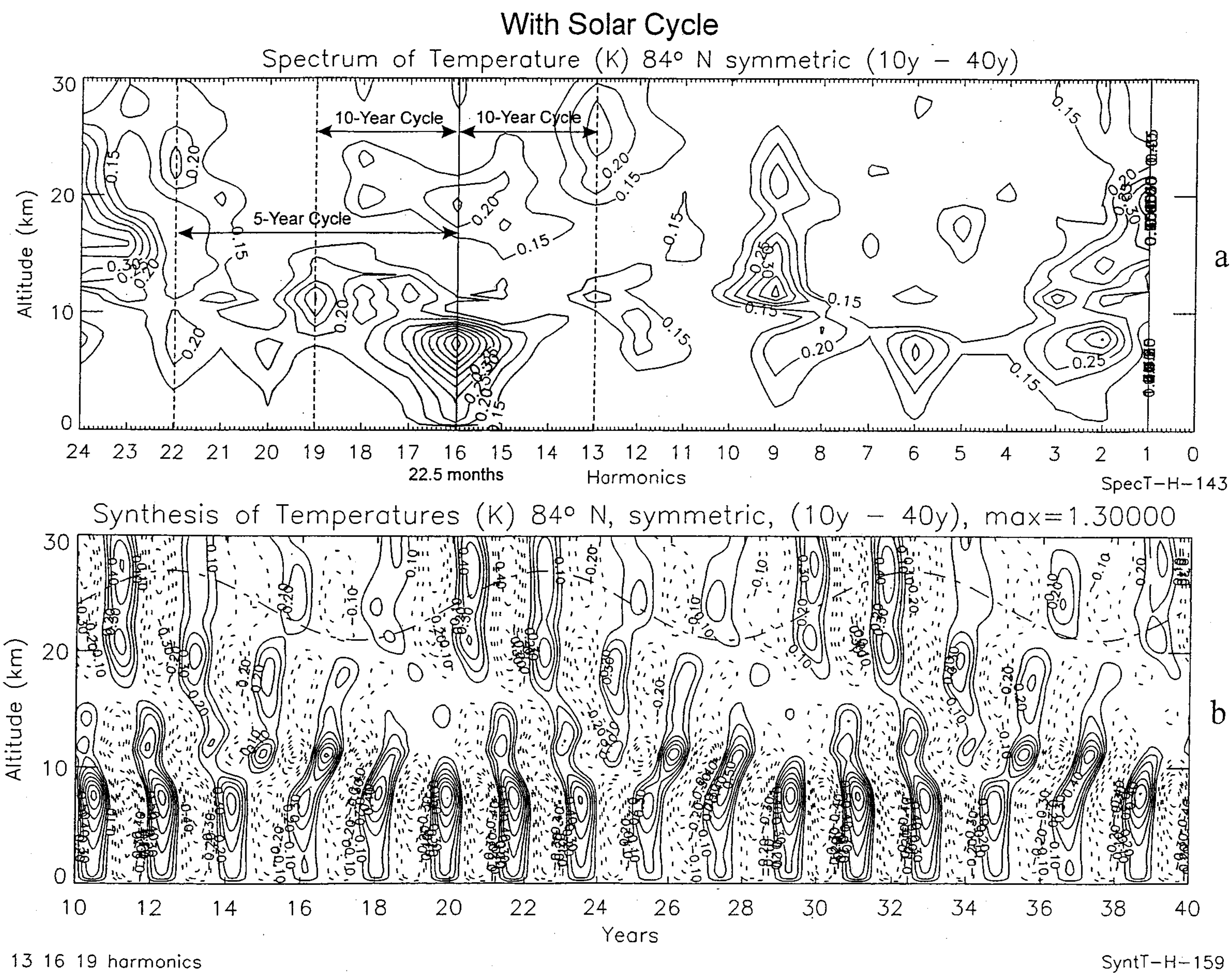
With Solar Cycle
Spectrum of Temperature (K) 84° N symmetric (10y – 40y)
10-Year Cycle
10-Year Cycle
5-Year Cycle
Altitude (km)
22.5 months
Harmonics
SpecT–H–143
a
Synthesis of Temperatures (K) 84° N, symmetric, (10y – 40y), max=1.30000
Altitude (km)
Years
13 16 19 harmonics
SyntT–H–159
b

Figure 5

Popular Summary:

The QBO as Potential Amplifier and Conduit to Lower Altitudes of Solar Cycle Influence
The solar cycle (SC) effect in the lower atmosphere has been linked observationally to the Quasi-biennial Oscillation (QBO), which is generated primarily by small-scale gravity waves. For a SC period of 10 years, the amplitude of the relative variations of radiative forcing is taken to vary from 0.2% at the surface to 2% at 50 km to 20% at 100 km and above. This model produces in the lower stratosphere a relatively large modulation of the QBO, which appears to be related to the SC and is in qualitative agreement with the observations by Salby and Callaghan (2000). Quasi-decadal oscillations, generated internally by the QBO interacting with the seasonal cycles, may interfere with or aid the SC effect.

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