

Wave-driven Equatorial Annual Oscillation Induced and Modulated by the Solar Cycle

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Abstract: Our model for the solar cycle (SC) modulation of the QBO (Mayr et al., 2005) produces a hemispherically symmetric 12-month Annual Oscillation (AO) in the zonal winds, which is confined to low latitudes. This Equatorial Annual Oscillation (EAO) is produced by interaction between the anti-symmetric component of SC forcing and the dominant anti-symmetric AO. The EAO is amplified by the upward propagating small-scale gravity waves (GW), and the oscillation propagates down through the stratosphere like the QBO. The amplitude of the EAO is relatively small, but its SC modulation contributes significantly to extend the effect to lower altitudes. Although the energy of the EAO is concentrated at low latitudes, prominent signatures appear in the Polar Regions where the SC produces measurable temperature variations. At lower altitudes, the SC effects are significantly different in the two hemispheres because of the EAO, and due to its GW driven downward propagation the phase of the annual cycle is delayed.

I. Introduction

The equatorial oscillations of the zonal circulation in the middle atmosphere, the Quasi-biennial Oscillation (QBO) and Semi-annual Oscillation (SAO), have in common - besides being confined to low latitudes -- that they are driven by waves. Lindzen and Holton (1968) demonstrated that the QBO (22 to 34 months period) can be generated with equatorially trapped planetary waves, and their theory was confirmed (e.g., Holton and Lindzen, 1972; Plumb, 1977; Dunkerton, 1985) and extended to the SAO (e.g., Dunkerton, 1979; Hamilton, 1986). Modeling studies with observed planetary waves subsequently revealed that small-scale gravity waves (GW) are more important (e.g., Hitchman and Leovy, 1988). Takahashi (1999) first succeeded in simulating the QBO with resolved GWs. But these waves generally need to be parameterized for global scale models and in particular for long-term simulations. Employing the GW parameterization developed by Hines (1997a, b), our model was among the first to simulate the QBO and SAO in the middle atmosphere (e.g., Mengel et al., 1995; Mayr et al., 1997).

Salby and Callaghan (2000) showed that the QBO in the lower stratosphere appears to be strongly affected by the solar cycle (SC). They analyzed more than 40 years of zonal wind measurements at 20 km and found distinct features in the power spectrum, which revealed a 29-month QBO modulated by the 11-year cycle and its second 5.5-year harmonic. A band pass filter or synthesis of the spectrum produced a SC correlated variation in the zonal wind power from 150 to 400 (m^2/s^2) or winds from 12 to 20 m/s.

This analysis has been the impetus for a 3D study with our Numerical Spectral Model (NSM), in which we simulated the QBO under the influence of the SC (Mayr et al., 2005). The model generates in the lower stratosphere a relatively large modulation of the QBO, which appears to come from the SC and qualitatively agrees with the observations.

It is the purpose of the present paper to report that the same model produces an equatorial annual (12 month) oscillation, which is induced and modulated by the SC. Following the approach taken in Mayr et al. (2005), we apply spectral analysis to describe this Equatorial Annual Oscillation (EAO).

II. Numerical Spectral Model (NSM)

The model discussed here is identical to that of Mayr et al (2005), and for completeness we describe its salient features. Assuming that the SC has a period of 10 years, the amplitude of relative variation in solar radiation is taken to vary exponentially

with height from 0.2 % at the surface, to 2 % at 50 km, to 20 % at 100 km and above. This SC modulation is applied in our Numerical Spectral Model (NSM), which was introduced by Chan et al. (1994). In the zonal mean (wave number $m = 0$), the NSM is energized by the absorption of EUV and UV radiation, and the heating rates for the mesosphere and stratosphere are taken from Strobel (1978). To reproduce qualitatively the observed zonal jets and temperature variations near the tropopause, a time independent tropospheric heat source is applied. Considering that the temperature perturbations are generally less than 10%, the radiative loss is described in terms of Newtonian cooling. We adopt the parameterization developed by Zhu (1989) but modify it so that the radiative relaxation rate is constant below 20 km. The solar tides are driven by the heating rates taken from Forbes and Garrett (1978).

As mentioned earlier, an integral part of the NSM is that it incorporates the Doppler Spread Parameterization (DSP) for GWs developed by Hines (1997a, b). The DSP introduces a spectrum of waves, which interact to produce Doppler spreading and thus affect the wave interactions with the flow. To account for enhanced advection in the tropics, a latitude dependent tropospheric GW source is adopted that peaks at the equator. The source is isotropic in the four cardinal directions and is assumed to be independent of season. A short vertical integration step of about 0.5 km is employed below 120 km to resolve the GW interactions with the flow. The model is truncated at the meridional and zonal wave numbers, $l = 12$ and $m = 4$, respectively.

III. Model Results

With the initial conditions set to zero, the NSM was run with and without the SC to cover a relatively limited time span of 40 years (4 solar cycles). In Figure 1 of Mayr et al. (2005), the computed zonal winds are presented at 4° latitude to show that the model reproduces the essential features of the QBO and SAO. The average QBO period is 22.5 months, which is near the lower limit of the observed range.

Ignoring the first 10 years to allow for spin-up, the remaining 30 years are analyzed to reveal the Annual Oscillation (AO) and its SC modulation. In Figure 1 we present the model results at 4° latitude for the solution that incorporates the above described SC forcing. In (a) the power spectrum is shown for the (hemispherically) symmetric zonal wind field, with the 12-month AO identified at the harmonic $h = 30$. Adjacent to this spectral feature of the AO are the signatures of the 10-year SC at $h = 33$ ($30 + 3$) and its second 5-year harmonic at $h = 24$ ($30 - 6$). (The 15-year side lobe is discussed later.)

The spectral features shown in Figure 1a represent an anomalous mode of the AO in that it is symmetric in contrast to the regular and dominant AO, which is (hemispherically) anti-symmetric. This is shown with the syntheses of the spectral features $h = 30$ and (30 ± 3) that are presented in Figure 1 for the symmetric (b) and anti-symmetric (c) AO components. Although the amplitude of the regular AO (c) is relatively large at 60 km, the weaker but symmetric AO (b) extends down to lower altitudes because it is driven also by wave-mean flow interactions.

A prominent feature of the symmetric AO is that it is strongly modulated by the SC, whose phase is shown with dashed line. The amplitude of the AO peaks close to the maximum of the SC forcing and, significantly, is in phase with the maximum in the amplitude of the SC modulated QBO as shown in Figure 3a of Mayr et al. (2005).

We believe that this anomalous mode of the AO is generated by the combined actions of the SC and GW interactions. The symmetric AO can be induced by nonlinear coupling between the anti-symmetric component of SC forcing and the regular and dominant anti-symmetric AO. This interaction produces a symmetric AO, and the GWs would organize it in the equatorial region to generate the downward propagating oscillation.

That this anomalous mode of the AO is indeed confined to low latitudes is shown with Figure 2a, where we present at 40 km a synthesis of the spectral harmonics employed in Figure 1b. As expected, the symmetric EAO peaks at the equator, and it virtually disappears at latitudes greater than 20° . The regular anti-symmetric AO shown in Figure 2b, in contrast, vanishes at the equator and increases towards mid latitudes. When the two AO components, the symmetric and anti-symmetric, are combined in Figure 2c, the resulting SC modulation reveals a remarkable asymmetry between the two hemispheres. The two hemispheres respond to the SC differently. The SC modulated AO amplitude is larger in the southern hemisphere around the years 12 and 13 during the SC maximum, and it is somewhat larger in the northern hemisphere during the minimum (and the hemispheric differences are not the same).

For comparison, we present in Figure 3 the numerical results from the model without SC. The spectrum is shown in Figure 3a, and it also contains signatures of a symmetric AO. In this case, there is no SC signature, but instead a prominent 15-year modulation is evident that is also seen and identified in Figure 1a. As illustrated in Mayr et al. (2003), GW node filtering can generate a 15-year beat period through the interaction between the anti-symmetric AO and a 22.5-month QBO, which applies to the present model. This 15-year oscillation is then anti-symmetric, and its interaction with the anti-symmetric AO produces the symmetric AO. Instead of the 10-year SC in Figure 1, an internally generated beat period is generating the EAO in Figure 3. The resulting AO is then amplified by the GWs, causing the oscillation to propagate down (Figure 3b).

As is the case for the SC modulation of the QBO, the EAO produces temperature variations in the Polar Regions. This is shown in Figure 4a, where we present the power spectrum for the symmetric temperature perturbations at 84° latitude. The 10-year and 5-year side lobes related to the SC are pronounced, and there is also a small signature of the 15-year beat period. A synthesis of the harmonics $h = 28, 30, 33$ then produces the SC modulation of the symmetric AO as shown in Figure 4b. The symmetric AO appears to propagate down from the upper stratosphere to produce a SC modulation of about 1 K in the temperature near the tropopause.

To reveal to global character of the symmetric AO, we present in Figure 5 the latitudinal variations of the synthesized temperatures for the harmonics $h = 28, 30, 33$ as in Figure 4b. In panels (a) and (b), the symmetric AO is shown for the northern hemisphere at 60 and 15 km respectively. At both altitudes, the temperature variations are larger at the pole, but the differences relative to the equator are still larger at 15 km. The phase progression suggests that the AO propagates from the equator towards the pole. This is consistent with our interpretation that the symmetric mode originates at equatorial latitudes where most of the energy resides, and it further justifies the label Equatorial Annual Oscillation although its signatures are apparent all over the globe.

As seen already from Figure 2c, a remarkable feature of this EAO is that it introduces a hemispheric asymmetry into the SC response. This is shown in Figure 5c, where we

present at 15 km for the northern and southern Polar Regions the synthetic temperature variations combining the symmetric and anti-symmetric AOs. In the northern and southern hemispheres, the AO amplitudes peak respectively before and after the SC maximum, and the amplitudes in both cases are different. And similar asymmetries appear in the minimum amplitudes of the AO.

IV. Conclusions

We have applied spectral analysis to describe the properties of the annual variations computed in a 3D modeling study (Mayr et al., 2005) that deals with the SC influence through the QBO. The model produces a hemispherically symmetric 12-month Annual Oscillation (AO) in the zonal winds, which is confined to latitudes around the equator and is strongly modulated by the SC. This Equatorial Annual Oscillation (EAO) is apparently produced by the interaction between the dominant anti-symmetric AO and the anti-symmetric component of SC forcing. The symmetric 12-months oscillation is effectively organized in the equatorial region, and it is amplified there by tapping the momentum from the upward propagating small-scale gravity waves (GW). Like the QBO, the EAO thus propagates down through the stratosphere and effectively transfers the SC signature to lower altitudes. As shown in Figure 1b, the amplitude of the EAO is not large, < 10 m/s, but its contribution to the SC effect is significant in the lower stratosphere in light of the small variations of solar radiation at these altitudes.

Although the energy of the EAO is concentrated mainly in the region around the equator, prominent signatures appear at high latitudes where the SC produces measurable variations in the temperature near the tropopause (Figures 4 and 5). As is the case for the QBO, the energy of this tropical AO is partially redistributed by the meridional circulation and planetary waves, presumably, to be focused onto the Polar Regions.

An important consequence of the EAO is that it introduces a hemispherical asymmetry into the SC response of the atmosphere as seen in Figures 2c and 5c. The strongest and weakest amplitudes in the SC modulation occur at different times in the northern and southern hemispheres. Due to the GW driven downward propagation of the EAO the resulting phase of the annual cycle is delayed at lower altitudes.

Another interesting feature of the EAO is that its response to the SC at equatorial latitudes is in phase with that of the QBO. This is apparent from a comparison between Figure 1b of the present paper and Figure 3a of Mayr et al. (2005). The SC modulation of the EAO may act as the pace maker for the QBO.

As shown in Figure 3, long-term variations can also be generated in the atmosphere without the SC. These could mask or mimic the SC forcing and thus complicate the interpretation of the model results, or observations.

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Figure Captions

Figure 1: (a) Power spectrum at 4° latitude for the (hemispherically) symmetric component of the zonal mean ($m = 0$) zonal winds obtained from the model with solar

cycle (SC) covering 30 years. The Annual Oscillation (AO) is identified along with the 10 and 5-year SC side lobes. (The 15-year spectral feature is discussed with Figure 3.) Syntheses of the spectral features $h = 27, 30, 33$ describe the SC modulation of the AO for the symmetric (b) and anti-symmetric (c) components. Although the anti-symmetric AO is relatively large (c), the weaker symmetric mode (b) propagates to lower altitudes due to gravity wave (GW) forcing.

Figure 2. Syntheses at 40 km altitude of the spectral features that describe the 10-year SC modulations of the AO for the symmetric (a) and anti-symmetric (b) components, and their combination (c). The symmetric (a) AO is confined to equatorial latitudes, while the anti-symmetric one (b) increases towards mid latitudes. Due to the presence of the symmetric component, the combined or total AO (c) reveals that the SC signatures in the northern and southern hemispheres are different.

Figure 3. (a) For comparison with Figure 1a, the power spectrum is shown from the solution without SC. Instead of the SC signatures, 15-year spectral features are evident, which are generated by the QBO of 22.5 months interacting with the anti-symmetric AO (Mayr et al., 2003). (b) Synthesis of $h = 28, 30, 32$ produces the corresponding symmetric equatorial oscillation that propagates down under the influence of GWs.

Figure 4. Similar to Figure 1 but for the temperature perturbations at 84° latitude. In (a) the spectrum is shown, and in (b) the synthesis describes the SC modulation.

Figure 5. Similar to Figure 2b but for the synthesized temperature variations. In (a) and (b), the symmetric SC modulations of the AO are shown at 60 and 15 km respectively. In (c) the combined, symmetric and anti-symmetric, temperature variations are presented at polar latitudes to show that the SC signatures in the two hemispheres are different.

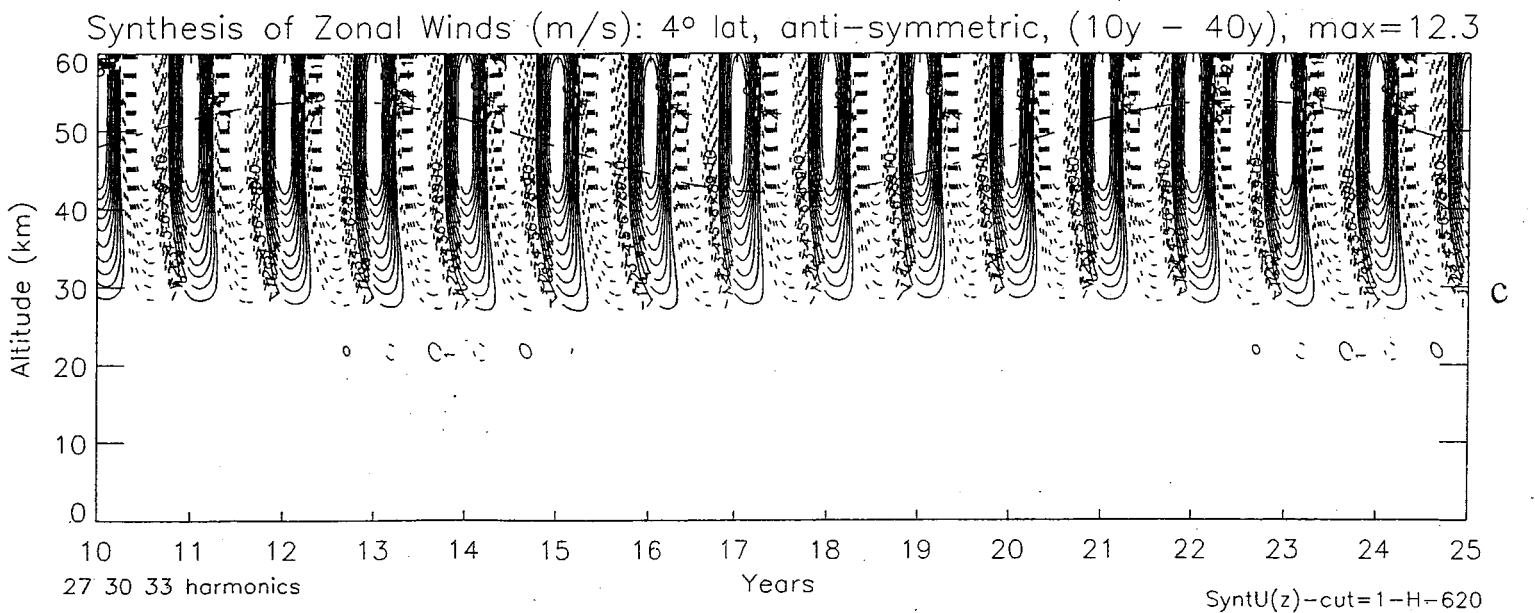
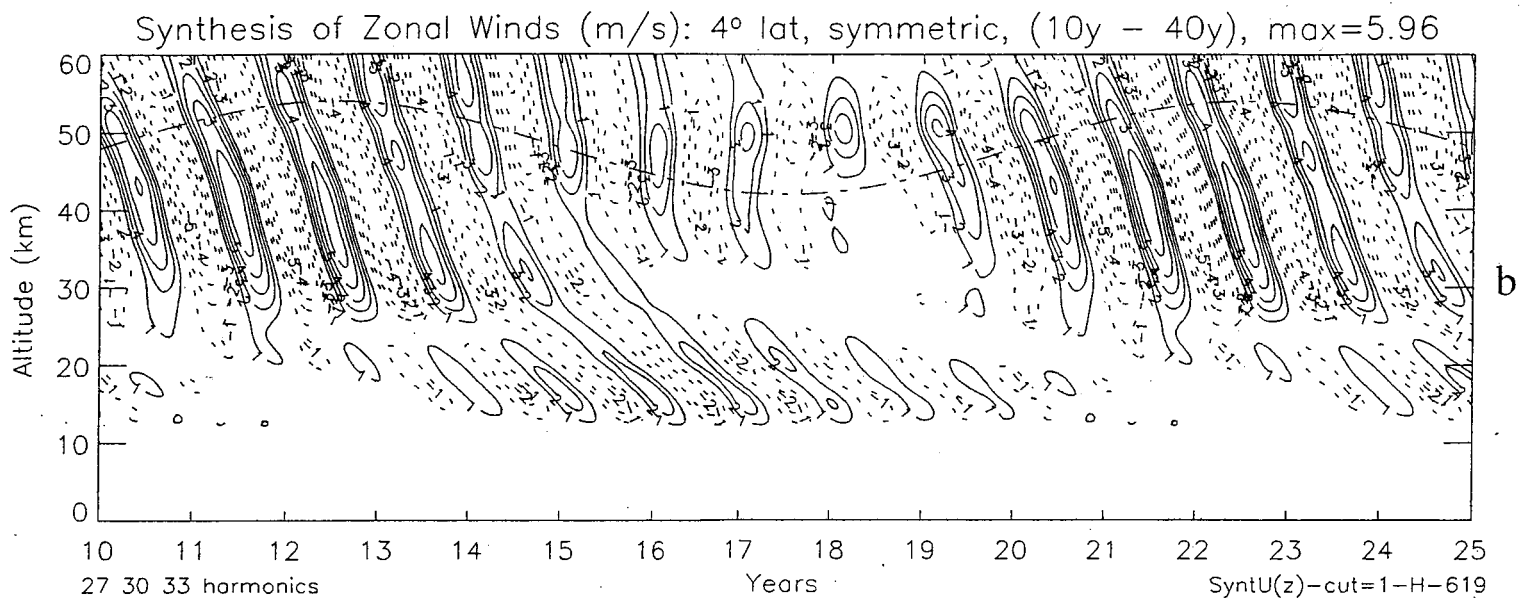
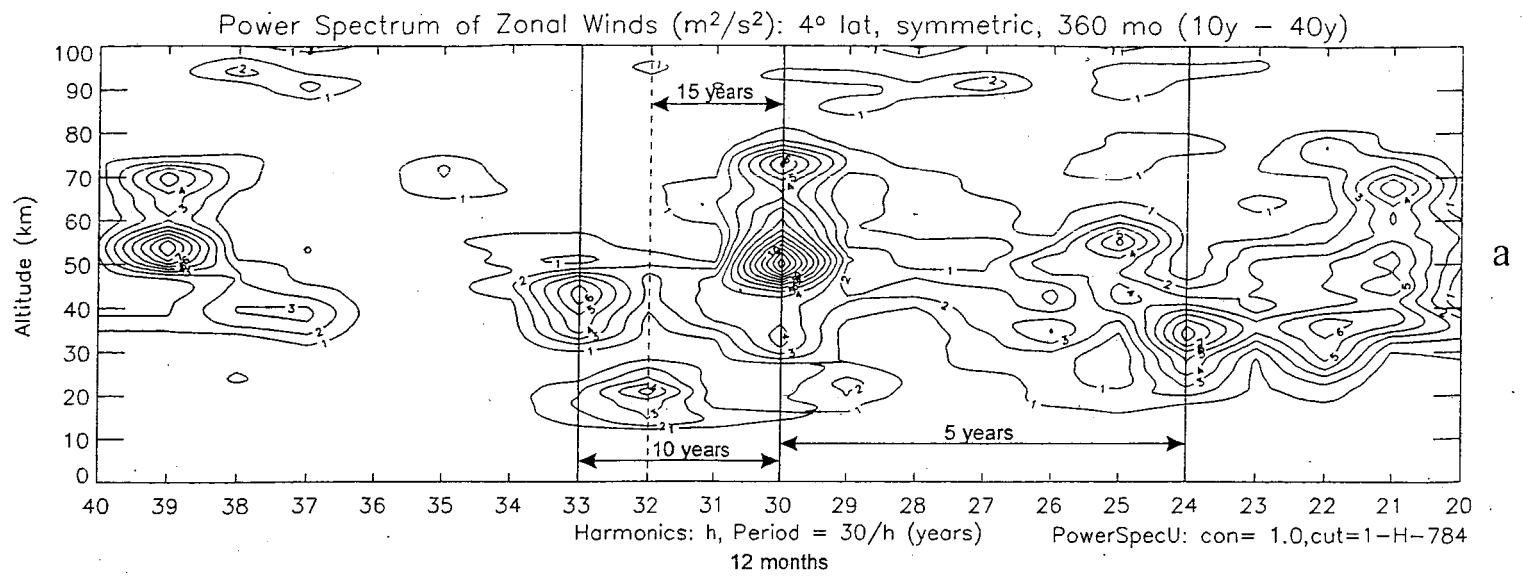
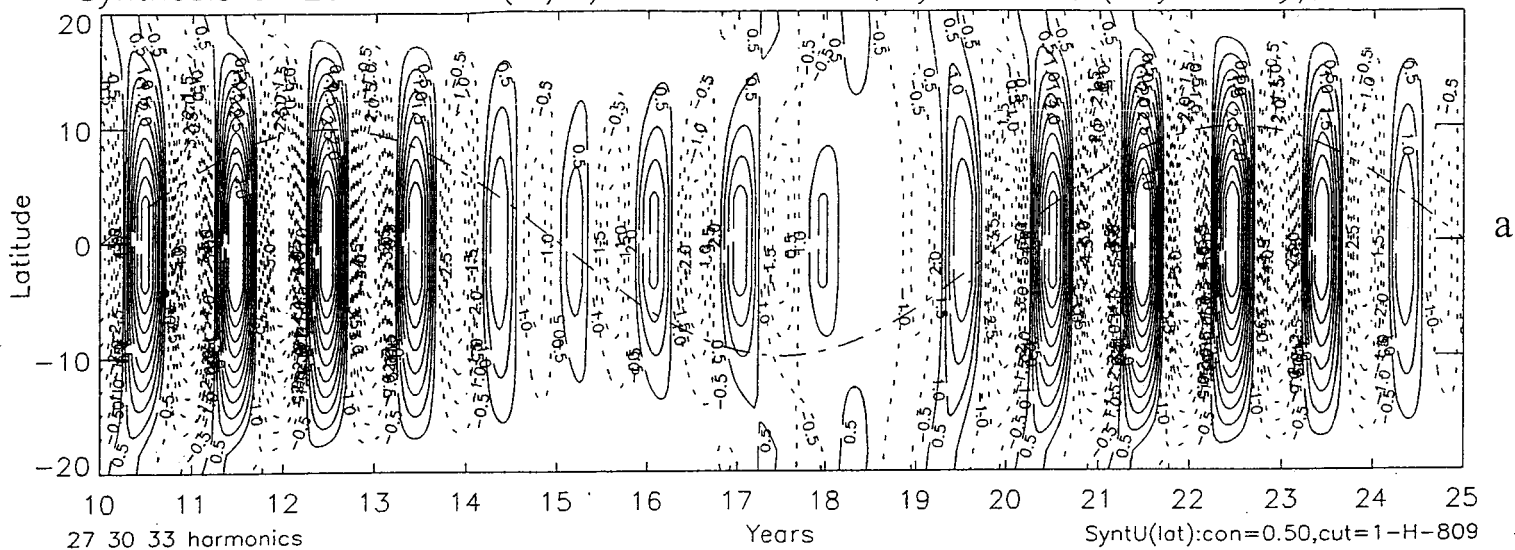
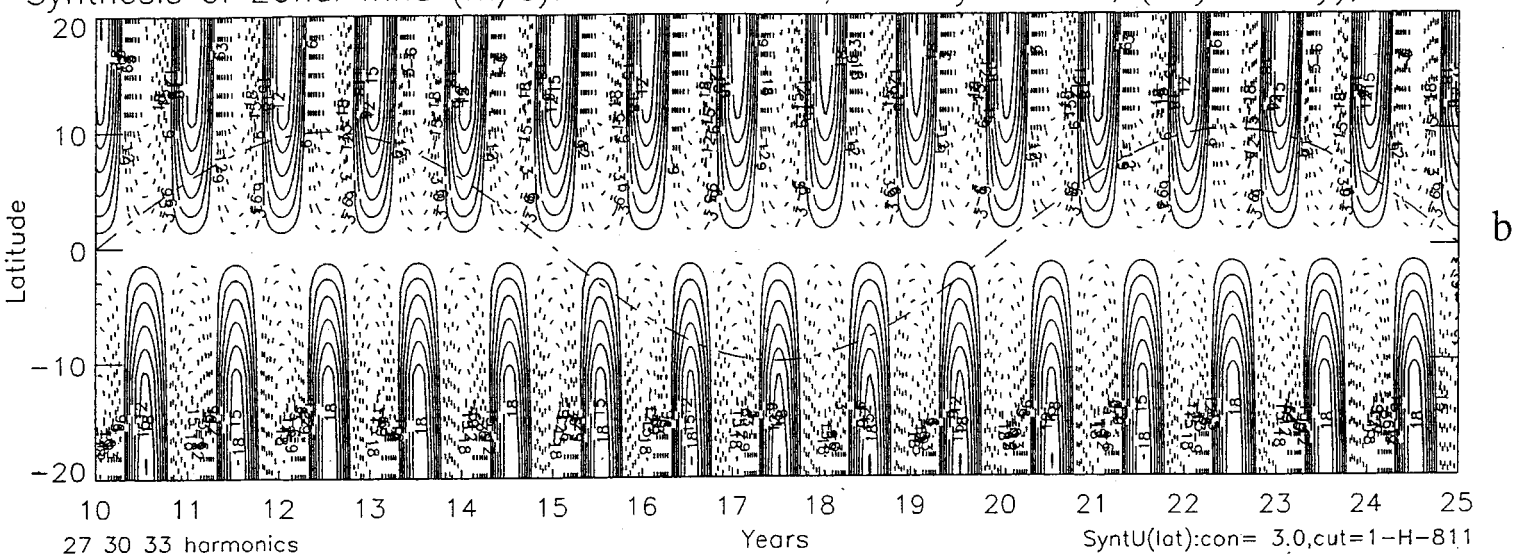


Figure 1

Synthesis of Zonal Wind (m/s): 40 km Altitude, symmetric, (10y – 40y), max=5.7



Synthesis of Zonal Wind (m/s): 40 km Altitude, anti-symmetric, (10y – 40y), max=28.



Synthesis of Zonal Wind (m/s): 40 km Altitude, total, (10y – 40y), max=28.

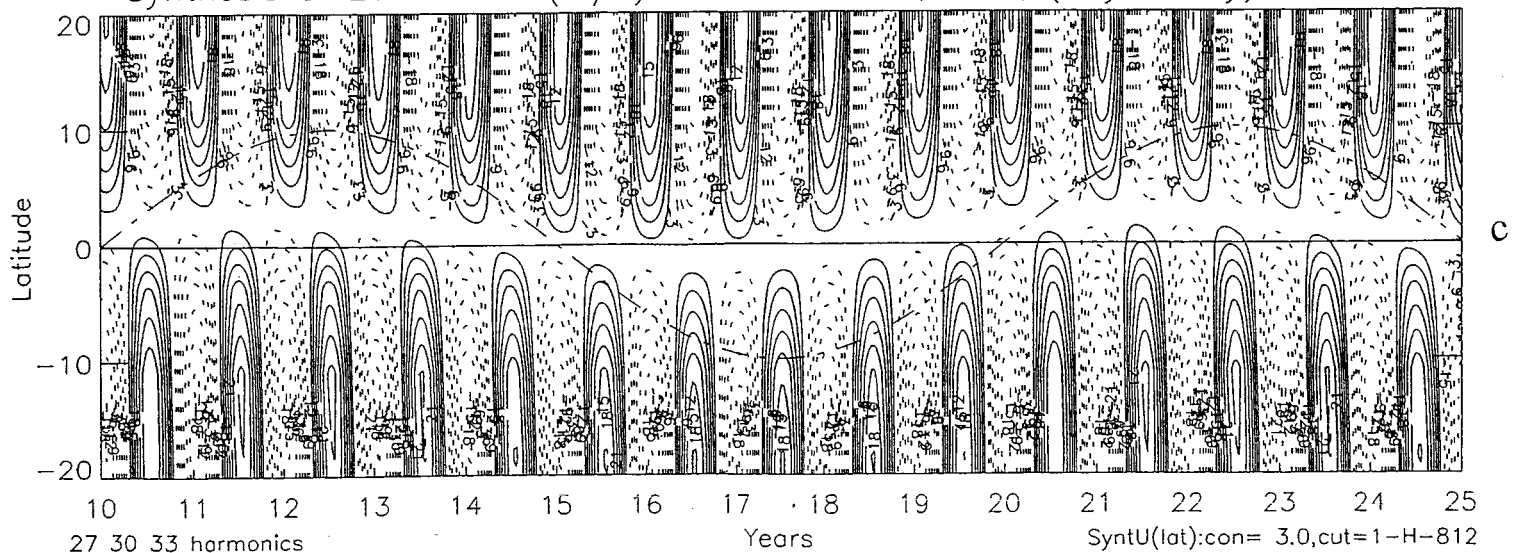


Figure 2

Without Solar Cycle

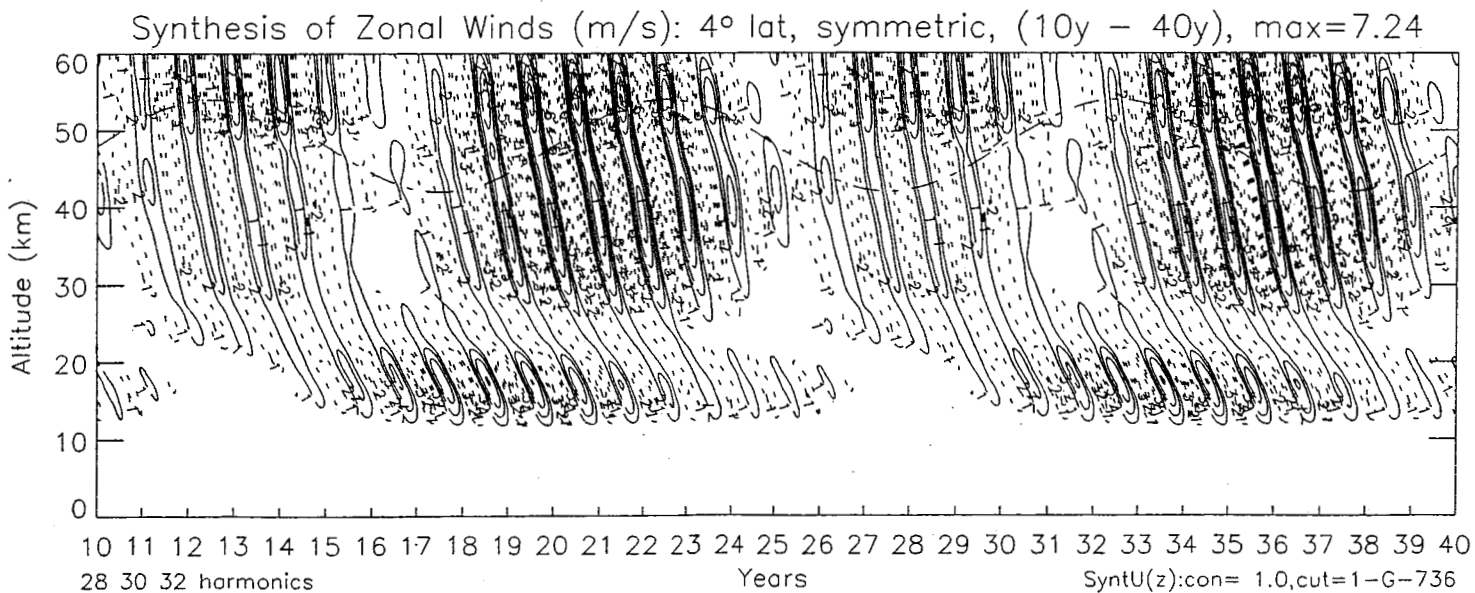
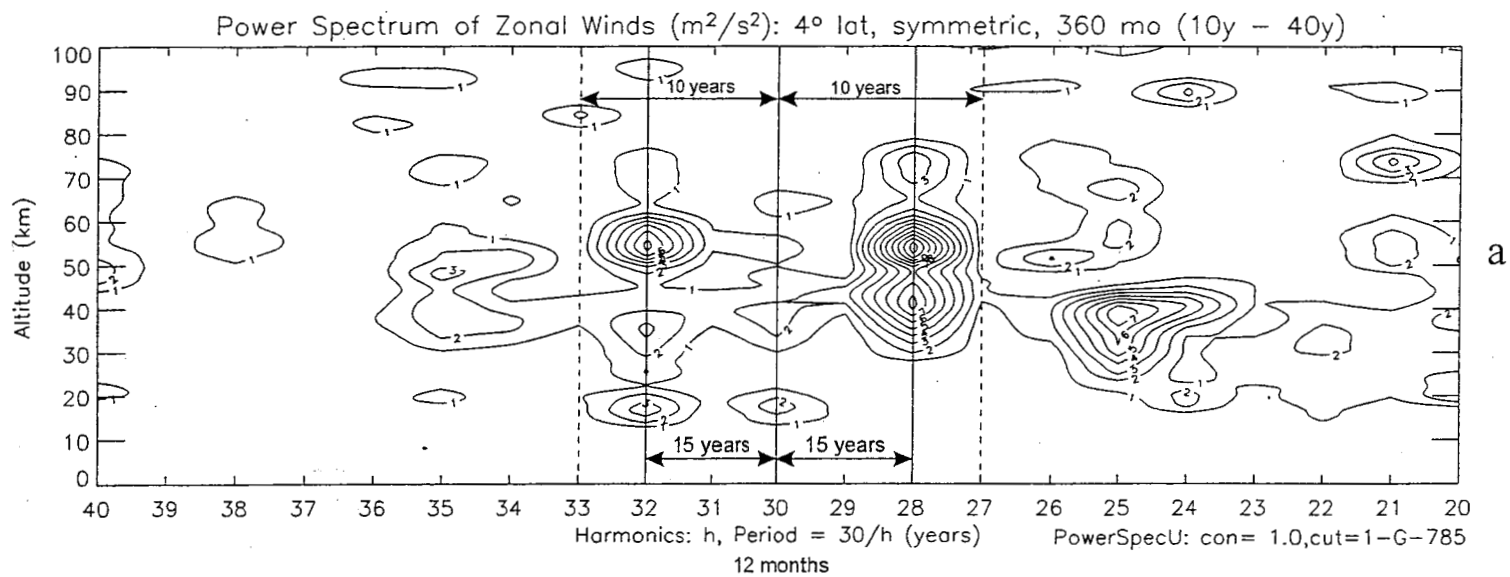


Figure 3

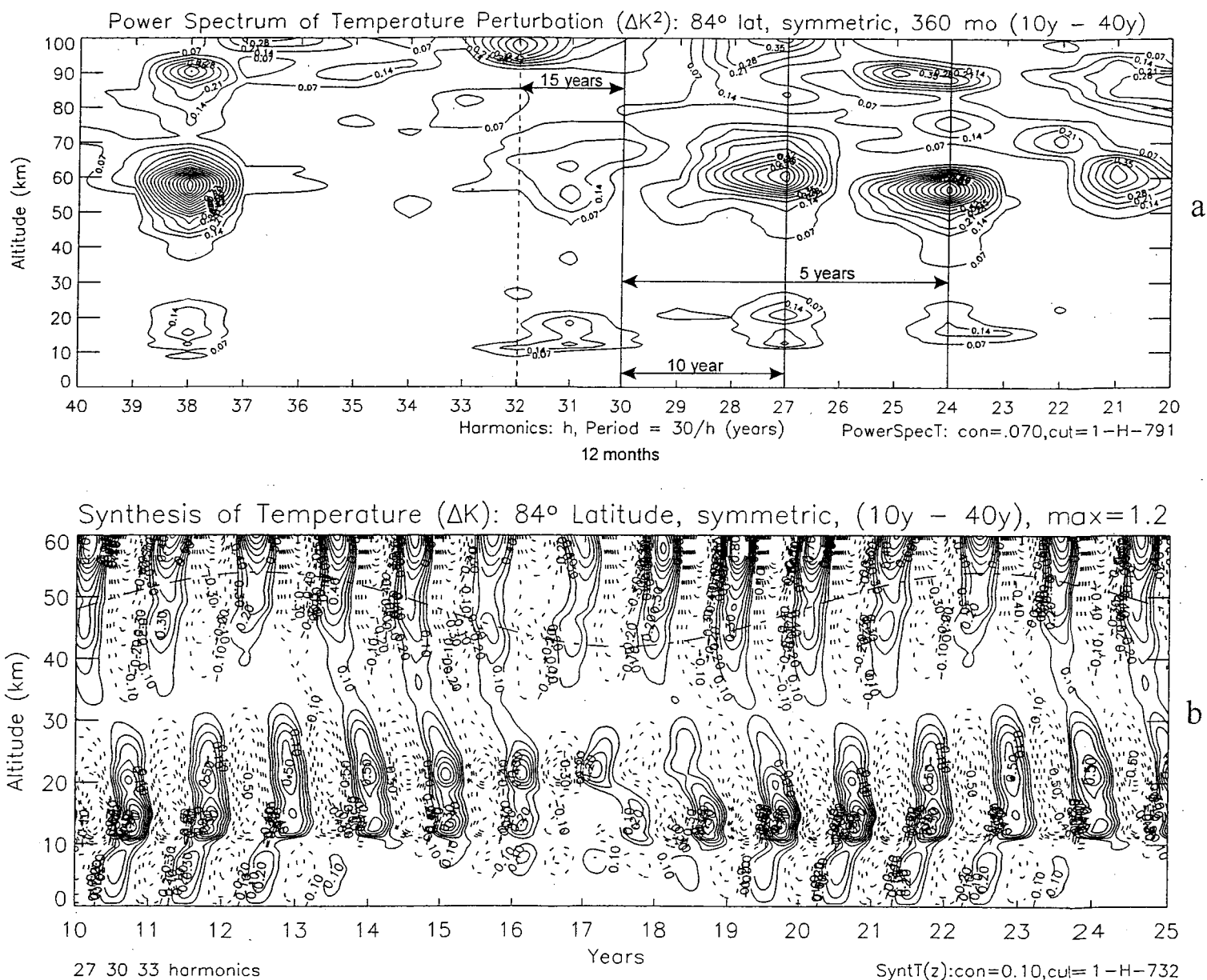


Figure 4

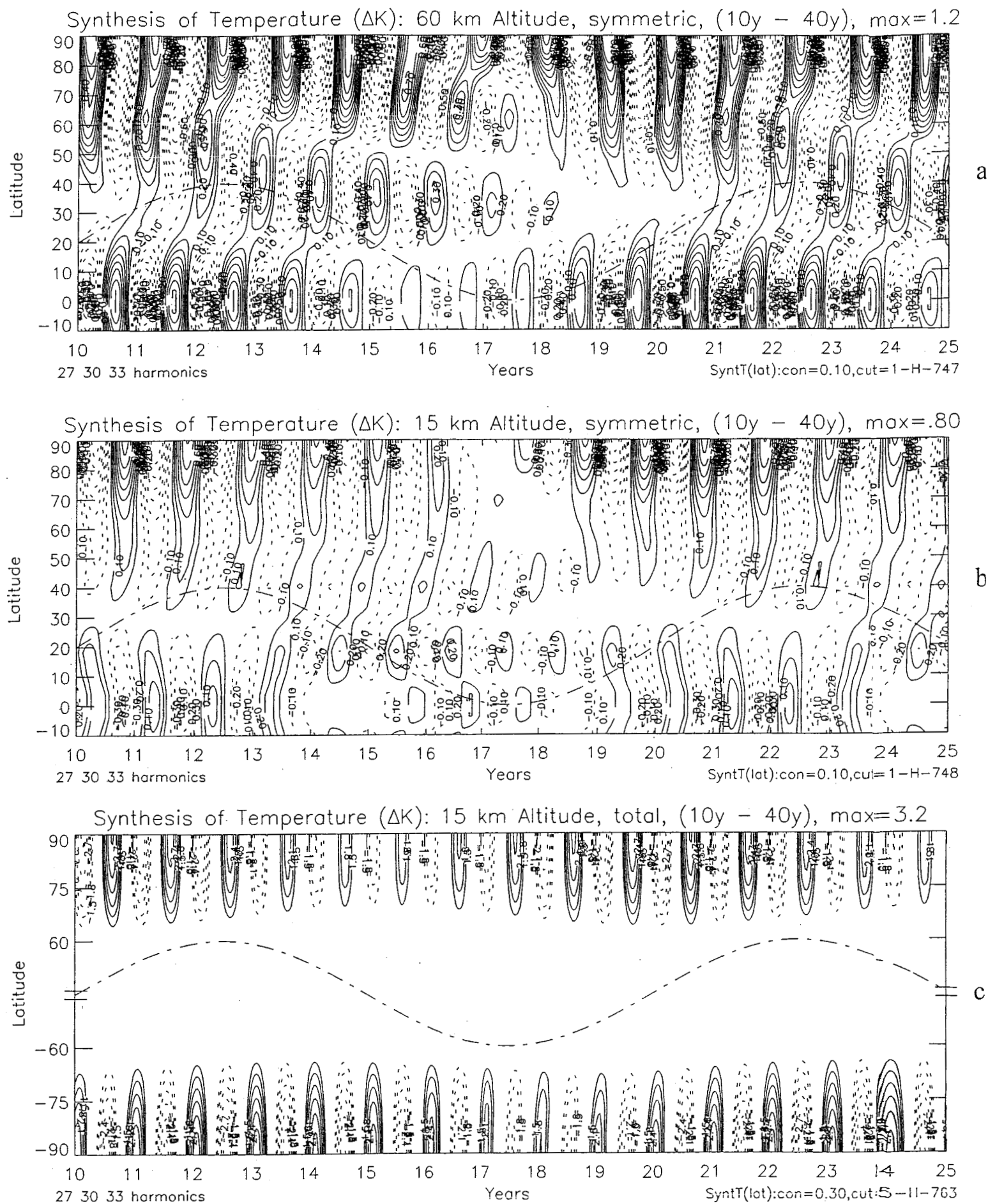


Figure 5

POPULAR SUMMARY

Wave-driven Equatorial Annual Oscillation Induced and Modulated by the Solar Cycle

We report that our model for the solar cycle (SC) modulation of the Quasi-biennial Oscillation (QBO) produces a hemispherically symmetric 12-month Annual Oscillation (AO) in the zonal winds, which is confined to low latitudes. This Equatorial Annual Oscillation (EAO) is produced by interaction between the anti-symmetric component of SC forcing and the dominant anti-symmetric AO. Due to wave-mean-flow interaction from small-scale gravity waves (GW), the EAO is amplified and propagates down through the stratosphere like the QBO. The amplitude of the EAO is relatively small, but its SC modulation contributes significantly to extend the effect to lower altitudes. Although the energy of the EAO is concentrated at low latitudes, prominent signatures appear in the Polar Regions where the SC produces measurable temperature variations. At lower altitudes, the SC effects are significantly different in the two hemispheres because of the EAO, and its GW driven downward propagation changes the phase of the annual cycle.

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