Solar-cycle Induced Jumps of the Quasi-Biennial Oscillation Period in Perpetual Solar Forcing Modeling Experiments

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Abstract

Using THINAIR model, we examine the mechanism of solar-cycle modulation on the Quasi-biennial Oscillation (QBO) period. Observational evidence for the existence of such a modulation--an anti-correlation between the westerly QBO duration and the solar flux--is controversial because it is found only during a period (1960s to early 1990s) contaminated by volcano aerosols (Salby and Callaghan, 2000; Soukharev and Hood, 2001; Pascoe et al. 2005; Hamilton, 2002; Fischer and Tung, 2007). However, this correlation in the longest available record was found to be near zero. In modeling, longer period runs without volcano influence can be obtained. The solar-cycle effect on the QBO period is rather subtle and complicated, with phase locking, beating and non-stationary behaviors. The experiments are run with perpetual solar minimum/maximum conditions, which help us capture the features in the realistic case of periodic forcing. Both in our model and observed data, the QBO period is constant with height. Under low solar forcing, the QBO period is phase-locked to a multiple (4) of Semi-Annual Oscillation (SAO) period. As solar forcing increases, the QBO period jumps with quantized multiple of the SAO periods, from 24 to 30 or 36 months. Because of this non-stationarity even under constant solar-cycle forcing, QBO periods do not respond one-to-one to changing solar flux in the realistic case of periodic solar-cycle forcing. Therefore the statistical significant QBO-solar relationship cannot be established without a much longer observational record. The mechanisms for solar modulation of QBO period are also discussed.

Model QBO and Comparison with NCEP

The THINAIR (Two and a Half dimensional INterActive Isentropic Research) is a chemical-radiative-dynamical model. The model has zonally averaged dynamics and includes the three longest planetary Waves [Kinnersley and Harwood, 1993]. The QBO source term in the momentum equation uses parameterization of wave momentum fluxes from Kelvin, Rossby-gravity and gravity waves [Kinnersley and Pawson, 1996]. These momentum sources also force the SAO above the QBO. UARS/SOLSTICE spectral irradiance observation is used as the 11-year solar cycle. Figure 1 (a) presents the modeling e-QBO and w-QBO duration versus pressure from 10 to 50 hPa under the SC-mean conditions. Near 10 hPa, the QBO period is dominated by its easterly phase. The e-QBO duration decreases and the w-QBO duration increases until they are about equal near 50 hPa. Figure 1 (b) shows the corresponding behavior in the NCEP reanalysis and demonstrates that the model has the correct behavior as compared to the reanalysis data.

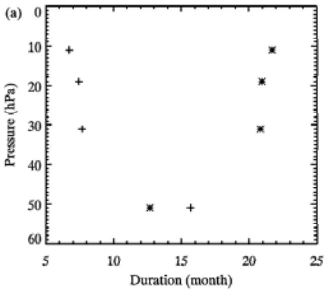

Figure 1. (a) Composite mean of e-QBO duration (*) and w-QBO duration (+) versus pressure from the THINAIR model. (b) Same as (a) from NCEP reanalysis.

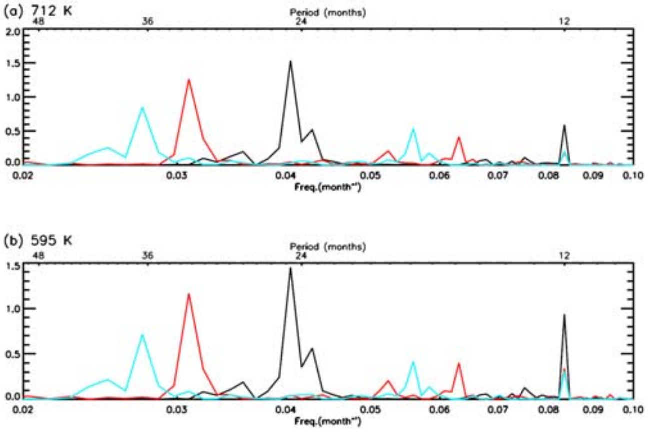

Figure 2. Fourier power spectra of the 70-year zonal wind time series from the THINAIR model; black line for 1×SC-min case; red line for 1×SC-max case; blue line for 2×SC-max case. (a) at potential temperature level 712 K (~15 hPa); (b) 595 K (~ 26 hPa);

Solar Cycle Influence on the QBO Period

With the time-dependent oscillatory solar forcing, determining the QBO period is not straightforward, since the period itself is changing with the solar cycle. However, with fixed solar forcing, the QBO period can be determined using its Fourier spectrum. We perform the simulation with the 1× to 3× SC-min/SC-max condition and the SC mean conditions. Figure 2 shows the Fourier spectrum of the 70-year time series of the QBO zonal wind at equator at various altitudes. The period of the QBO was showed to be independent on height. The results reveal a QBO Period of 25.08 months for 1×SC-min (black line), 31.85 months for the 1×SC-max (red line) and 36.01 months for the 2×SC-max (blue line) conditions. Thus, the period of the QBO is unambiguously lengthened as the solar flux increases.

In Figure 3 (a) we plot the QBO period as a function of the solar index in units of solar flux (one unit represents one half of the difference of solar flux between the SC-max and SC-min). This establishes that the period of the QBO generally increases as the solar flux increases. The QBO period is phase-locked with the 4 SAO periods (so that it is also phase-locked with the annual cycle). Once the QBO period was locked in a 24 months at 2×SC-min, further reduction of the solar flux to 3×SC-min does not seem to be able to change its period, thus forming a flat ledge in Figure 3 (a). In the other cases, the averaged QBO period increases when perturbed by increasing solar fluxes.

Above 30 hPa, it is the easterly duration which varies with solar flux (Figure 3 (b) and (c)), while below 30 hPa it is the westerly duration that varies with solar flux (Figure 3 (d)), consistent with the observational result of Fischer and Tung [2007].

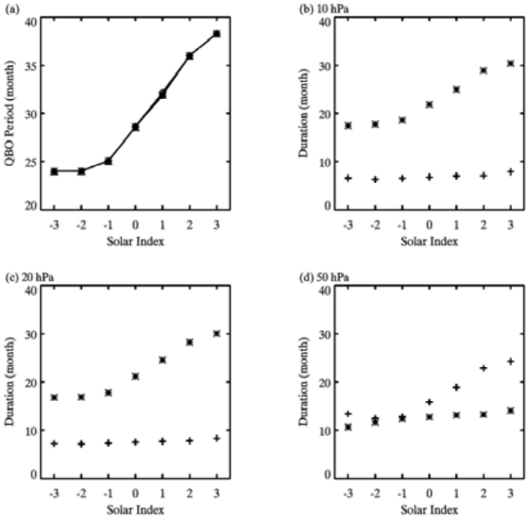

Figure 3. (a) QBO period as a function of solar-cycle forcing obtained using the THINAIR model for five levels from 7-80 hPa. Lines overlap, showing that the period does not change with height. Composite mean of e-QBO duration (*) and w-QBO duration (+) versus solar forcing (b) 10 hPa, (c) 20 hPa, (d) 50 hPa.

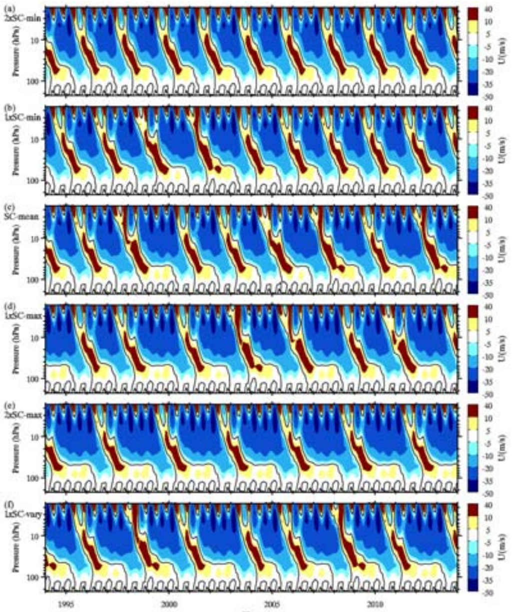

Figure 4. Time-height section of the equatorial monthly-mean zonal wind component (in m s^{-1}) from the THINAIR model simulation. The individual QBO period is synchronized with SAO near stratopause. The black line is the zero-wind line. (a) 2×SC-min perpetual condition; (b) 1×SC-min perpetual condition; (c) SC-mean perpetual condition; (d) 1×SC-max perpetual condition; (e) 2×SC-min perpetual condition. (f) under realistic periodic solar-cycle forcing from 1×SC-min to 1×SC-max.

The QBO period is quantized in units of SAO period. Panel (a) in Figure 4 shows the simplest case, a QBO period locked in 4 SAO periods for 2×SC-min. Panel (b) shows the case for 1×SC-min. The QBO period comprises 4 SAO periods most of the time, and occasionally there is one or two QBO periods consisting of 5 SAO periods. As a result, the average QBO period is 25.08 months. Apparently the solar forcing is not strong enough to force the QBO period into 5 SAO periods permanently. There is also the possibility that an odd multiple of SAO periods is not stable with respect to annual-cycle perturbation. Panel (d) shows the result with 1×SC-max condition. Similar to the 1×SC-min case, the time series is also non-stationary. A QBO period can comprise of mostly 4 and 6 and occasional 5 SAO periods, yielding an average QBO period of31.85 months. Panel (c) shows the case of SC-mean (without solar-cycle forcing) and it appears to behave approximately as the average of 1×SC-min and 1×SC-max cases, with an average period of 28.59 months, which comprises mostly 5 and 4 SAO periods with an occasional 6 SAO periods. Panel (e) shows the behavior for 2×SC-max, where the QBO period time series becomes stationary again and phase-locked into 6 SAO periods.

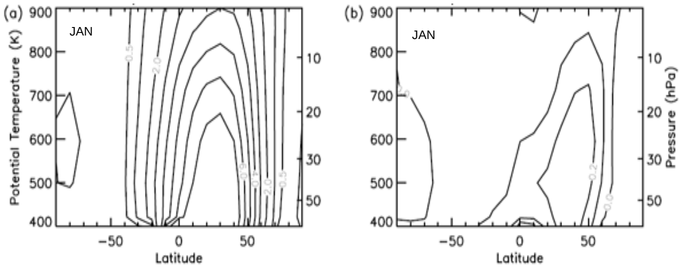

Figure 5. (a) Mass stream function on isentropic surfaces in units of 10^9 kg s^{-1} under 1 × SC-min condition. (b) The difference between the composites of the 1 × SC-max and 1 × SC-min. Both figures are for Jan.

Mechanisms for solar modulation of QBO period.

The isentropic stream-function for the Brewer-Dobson circulation in the stratosphere in January shows a strengthened Brewer-Dobson circulation during SC-max conditions as compared to SC-min conditions (figure 5). A stronger upwelling branch of the Brewer-Dobson circulation over the equator slows the descent of the QBO shear zone and extends the QBO period.

A second mechanism is a radiative perturbation of the SAO-QBO transition region due to the ozone feedback.

Conclusions

1) The QBO period is lengthened during solar maxima. 2) The non-stationary behavior of the QBO period even if the solar flux is held constant. 3) A tendency of the QBO period to synchronize with the SAO period. 4) 24 months and 36 months QBO periods are more stable because there is also a synchronization with the annual cycle. 5) There are temporary (non-stationary) quantum jumps of the QBO period by a SAO period when the stratopause region is perturbed by the solar cycle.

Reference:

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