ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 20, NO. 2, 2003, PP. 303–309

Impact of the 11-yr Solar Activity on the QBO in the Climate System

Hengyi WENG* (翁衡毅)

LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029

(Received November 11, 2002; revised January 13, 2003)

ABSTRACT

The QBO (quasi-biennial oscillation) in the climate system, with a mean cycle-length slightly above or below 2 years, is studied in a simple forced dynamical system. The fundamental cause of the quasi-biennial periodicity of the QBO is nonlinear resonance of the system to the seasonal forcing that is modulated by the 11-yr solar cycle. For a given nonlinearity, the cycle-length and the amplitude of the QBO depend on the intensity of both the unmodulated seasonal cycle and the 11-yr solar cycle, which may be one of the reasons why the QBO properties in climate vary with time and space.

Key words: QBO, seasonal forcing, solar modulation, nonlinear resonance

The term QBO (quasi-biennial oscillation) is generic for all quasi-periodic oscillation phenomena having a quasi-biennial (QB) periodicity, with a mean cycle-length slightly above or below 2 years. Thus, it may be used for any QBO observed in the climate system. The most prominent QBO in the atmosphere is found in the equatorial stratospheric zonal wind with a mean cycle-length of 26 or 28 months, depending on locations and sampling periods (Quiroz, 1981). Signals with a similar QB periodicity have also been observed in other parameters in the climate system, such as sea-level pressure, land- and sea-surface temperature, East Asian monsoon rainfall, polar stratospheric temperature, and sub-arctic river sediments, etc. (Landsberg et al., 1963; van Loon and Rogers, 1978; Trenberth, 1980; Yasunari, 1989; Rasmusson et al., 1990; Sonett et al., 1992; Baldwin et al., 2001). Intensive QBOs have been found in some extreme climate events such as the 1997/98 El Niño/La Niña and the 1997/98 severe summer drought/flood in China (Lau and Weng, 2001). The widely existing QBO phenomena in the climate system suggest that there would be a universal cause for the QB periodicity in any QBO no matter whether it appears in the stratosphere, in the troposphere, or in the oceans or rivers, and whether it is in the tropics, in the extratropics, or in the polar regions.

Most studies have attributed the QB periodicity to the interactions between different parts of the climate system (Lindzen and Holton, 1968; Brier, 1978; Chang and Li, 2000; Kim and Lau, 2001; Li et al., 2001; Meehl and Ablaster, 2002). These interactions alone, though important to complete a QBO cycle physically, were not able to explain why the observed QB periodicity is slightly above or below 2 years. The QB periodicity is different from the biennial periodicity; the latter results from a nonlinear resonance of the climate system to the seasonal forcing (Brier, 1978; Jin et al., 1994; Tziperman et al., 1995). Moreover, the QB periodicity is not simply a flip-flop biennial phenomenon with a changing phase from one year to the next.

Earlier studies found QBOs showing close relationships with seasonal variation in the atmospheric phenomena, e.g., in the Asia-Australia and Indo-Pacific monsoon (Chang and Li, 2000; Meehl and Ablaster, 2002). Some QBOs were modulated on the decadal timescale, including the 11-yr solar cycle (Quiroz, 1981; Labitzke and van Loon, 1988; Kodera, 1993; Salby and Callaghan, 2000; Hamilton, 2002). As to the relationship between different QBO phenomena, some studies suggested that the QBO in the troposphere is independent from the one in the equatorial stratospheric zonal wind, while some others considered the equatorial stratospheric QBO as a source for the QBOs in the troposphere, although the fundamental cause of the QB periodicity in the equatorial stratospheric QBO itself is still in question (Baldwin et al., 2001). This paper aims at illustrating the possible fundamental cause for the QB periodicity of the generic

---

*E-mail: weng@lasg.iap.ac.cn

QBO in the climate system, not at finding any dynamical/physical interaction between different parts of the climate system involved in any particular QBO.

It is speculated that the nonlinear resonance of the climate system to the seasonal forcing that is modulated by the 11-yr solar cycle is essential for the observed QB periodicity. To show this point, following Lorenz (1964), we use a very simple forced nonlinear system, a first-order quadratic difference equation, as the governing equation, leaving all the non-essential factors out of focus. The system is

$$X_{n+1} = rX_n(1 - X_n) + F_n\ , n = 1, 2, \ldots\ , \quad (1)$$

and the forcing term F_n is expressed as

$$F_n = A_1[1 + A_{11}\cos(\Omega n)]\cos(\omega n) \quad (2)$$

$$= A_1\cos(\omega n) + A_1A_{11}[\cos(\omega + \Omega)n]/2$$
$$+ A_1A_{11}[\cos(\omega - \Omega)n]/2\ , \quad (3)$$

where

X_n: a "climate" variable between 0 and 1,

n: the index of iteration with a "monthly" step,

r: a parameter for internal nonlinearity,

ω and Ω: the frequencies of the "seasonal" and "solar" cycles, respectively, and

A_1 and A_{11}: the amplitudes of the "seasonal" and "solar" cycles, respectively.

The formulation of the forcing term is based on the knowledge from satellite observations that the "solar constant" is varying with the 11-yr solar cycle (Lean, 1991). This simple dynamical system captures much of the mathematics of the fundamental cause of the QB periodicity in the generic QBO and its variability observed in the climate system, which will be illustrated by the following experimental results.

We run experiments with the system at different combinations of A_1 and A_{11} for a fixed nonlinearity of $r = 3.3$ and the initial value of $X_1 = 0.001$. For each case, we iterate the system for 500 years (6000 steps or months) and then save the following 8192 monthly data points as the time series for complex Morlet wavelet analysis (Lau and Weng, 1995). To eliminate the edge effect on the results, we choose the middle 2048 data points for further study.

The regimes in the free system, $F_n = 0$ in Eq.(1), for different nonlinearity were presented previously (May 1976; Weng and Lau, 1994). At $r = 3.3$, only a "period-2" (2-month) oscillation was observed. There was no other timescale in the system due to internal dynamics. In the forced system, when the forcing has the seasonal variation only, we find the biennial oscillation (BO) with the 2-yr cycle-length and other interannual and longer timescales as well as sub-seasonal timescales.

Table 1 lists the responding timescales, limited to longer than one year only, observed in the system in nine cases as the intensity of the seasonal forcing (A_1) increases while the 11-yr solar modulation is absent ($A_{11} = 0$). A small change in the intensity of the seasonal forcing may result in different multi-scale oscillations with different intensities of the BO and/or shifts between different timescales of ENSO (El Niño-Southern Oscillation), e.g., a shift between the 4-yr component and the coexisting 3-yr and 6-yr components. The responding timescales listed in Table 1 are similar to those previously studied theoretically for a climate system without any influence from solar activity (e.g., Jin et al., 1994). Though the seasonal forcing alone may excite the subharmonics at 2-yr, 3-yr, 4-yr, 6-yr, and even decadal-interdecadal timescales in these experiments, there is no timescale slightly above or below 2 years, which should be there for the observed QB periodicity of any QBO in the climate system. Note that the number of timescales is increased and then decreased with A_1, so that the relationship between the number of the responding timescales and the intensity of the seasonal forcing is not linear.

Table 1. The regimes of Eq.(1) with observed timescales as A_1 increases while keeping $A_{11} = 0$

A_1	Observed timescales
0.095	No timescale longer than 1 year.
0.096	Stationary 2-yr timescale only.
0.0971	Stationary 2-yr and 4-yr timescales–the average timescale of ENSO.
0.0975	Nonstationary 2-yr, as well as 3-yr and 6-yr timescales with regularity.
0.1	Aperiodic, dominated by the 2-yr timescale.
0.15	Aperiodic, dominated by the 4-yr timescale.
0.22	Stationary 2-yr and 4-yr timescales.
0.225	Stationary 2-yr timescale only.
0.223	No timescale longer than 1 year.

When the seasonal forcing is modulated by the 11-yr cycle, $A_{11} \neq 0$ in Eq.(2), the regimes of the system at the same values of A_1 in Table 1 will be changed. Based on (3), beside the seasonal component in the forcing, ω, now there are two additional periodic forcing components, caused by the 11-yr solar modulation, with timescales of 0.9 years ($\omega + \Omega$), and 1.1 years ($\omega - \Omega$), respectively. The nonlinear resonance of the system to the three-scale forcing as well as the second- and higher-order interactions among them result in many additional timescales beside those without the 11-yr modulation, including the timescales of $\omega/p \pm \Omega/q$ and Ω/q, where p, q (=1, 2, ...) are integers. Here we only present two sets of experiments in Fig. 1; each has a fixed seasonal forcing ($A_1 = 0.0971$ or $A_1 = 0.22$) but different solar modulation ($A_{11} = 0.01, 0.02, 0.03$ and 0.05, respectively).

In the set with a weaker seasonal forcing ($A_1 = 0.0971$), when the solar modulation is also weak ($A_{11} = 0.01$), as shown in Fig. 1a, the BO ($\omega/2$) component is dominant. A pair of discernable weak QBO components (1.7 and 2.4 years) occasionally appears when the BO is absent. The pair of the QBO components is the sidebands of the BO excited by the 11-yr modulation: $\omega/2+\Omega$ for the 1.7-yr component while $\omega/2-\Omega$ for the 2.4-yr one. In fact, a sideband of the 3-yr component may be very close to a 2-yr sideband. For example, the timescales of the components $\omega/3+\Omega$ ($\approx$2.35 years) and $\omega/2 - \Omega$ ($\approx$2.44 years) are both roughly 2.4 years. There are also weak components around 3, 4, 5.5, and 11 years that are nonstationary but with regularity, modulated on the 44-yr timescale ($\Omega/4$), which may be mistaken as "non-regular" if we did not look at them carefully, especially if taking a shorter data record. The short-lived weak 2.6-yr and 2.8-yr components are the sidebands of the 3-yr component due to the 22-yr and the 44-yr modulation, $\omega/3 + \Omega/2$ and $\omega/3 + \Omega/4$, respectively. In practice, a looser definition of QBO with the "2–3-yr variability" has been used in many studies. Here we include the 2.6-yr and 2.8-yr components in the "QBO components" based on the looser definition. Thus, the QB periodicity itself has multiple timescales. In Fig. 1b ($A_{11} = 0.02$), both the BO and the QBO components are regularly amplitude-modulated on the 11-yr (weaker) and the 5.5-yr (stronger) timescales. In Fig. 1c ($A_{11} = 0.03$), the nonstationarity of the BO and the QBO components becomes more complicated than that in Fig. 1a but still with regularity. Various components on the interannual timescales are simultaneously modulated on both the 11-yr and the 44-yr timescales. Besides, there are interdecadal timescales, which were absent in both Figs. 1a and 1b. In Fig. 1d ($A_{11} = 0.05$), the regime exhibits an aperiodic nature; at least in our time domain the system does not repeat itself on any timescale.

The regimes in the set with the stronger seasonal forcing ($A_1 = 0.22$) are very different from those with the weaker forcing. The regimes in Fig. 1e and Fig. 1f are regular, yet there are more timescales in Fig. 1f. An apparent signal around the 2-yr timescale is dominant through the time domain with its amplitude being slightly modulated on the 11-yr timescale. All the other interannual timescales are amplitude-modulated on the 11-yr and the 22-yr timescales. In Fig. 1g, the BO and the QBO components are nonstationary without regularity, or aperiodic. The 1.8-yr and 2.2-yr QBO components are related to $\omega/2 + \Omega/2$ and $\omega/2 - \Omega/2$, respectively. In the cases discussed so far for this set, the number of the responding timescales in the system increases with the intensity of the 11-yr modulation. However, from Fig. 1g to Fig. 1h, the number of the timescales is reduced. In Fig. 1h, the 2-yr, the 3-yr, and the 5.5-yr components and their sidebands become regularly modulated on the 11-yr timescale. No components are observed around the 4-yr and other longer timescales except for the 11-yr solar timescale. The results show again that the number of the responding timescales in a nonlinear system does not always increase with intensity of the external forcing.

In Fig. 1, we decomposed the time series into components on different fixed timescales, including the multiple QBO components. In observational data analysis, we often study a QBO signal by its cycle-length, amplitude, etc. based on a band-passed time series that is limited to include only the QBO components. We want to know how the cycle-length and the amplitude of the QBO vary with time, because the phase condition of an intensive QBO may be important to the timing of an extreme climate event. Fig. 2 will show the temporal behaviour of the band-passed QBO (20–36 months) time series at two parameter settings that were used for Figs. 1b and 1f where the two regimes have different regularity under the same solar modulation but different seasonal cycles. It is to illustrate how the intensity of the seasonal forcing influences the cycle-length and the amplitude of a QBO signal when an 11-yr solar modulation exists.

In Fig. 2a ($A_1 = 0.0971$), the cycle-length of the QBO varies between 21 months (1.7 years) and 36 months (3 years) with a mean cycle-length around 28 months (2.4 years), which is close to the mean cycle-length of the equatorial stratospheric QBO (Baldwin, et al., 2001) and other QBOs in the climate system (van Loon and Rogers, 1978; Trenberth, 1980). The QBO's amplitude is modulated by both the 11-yr cycle

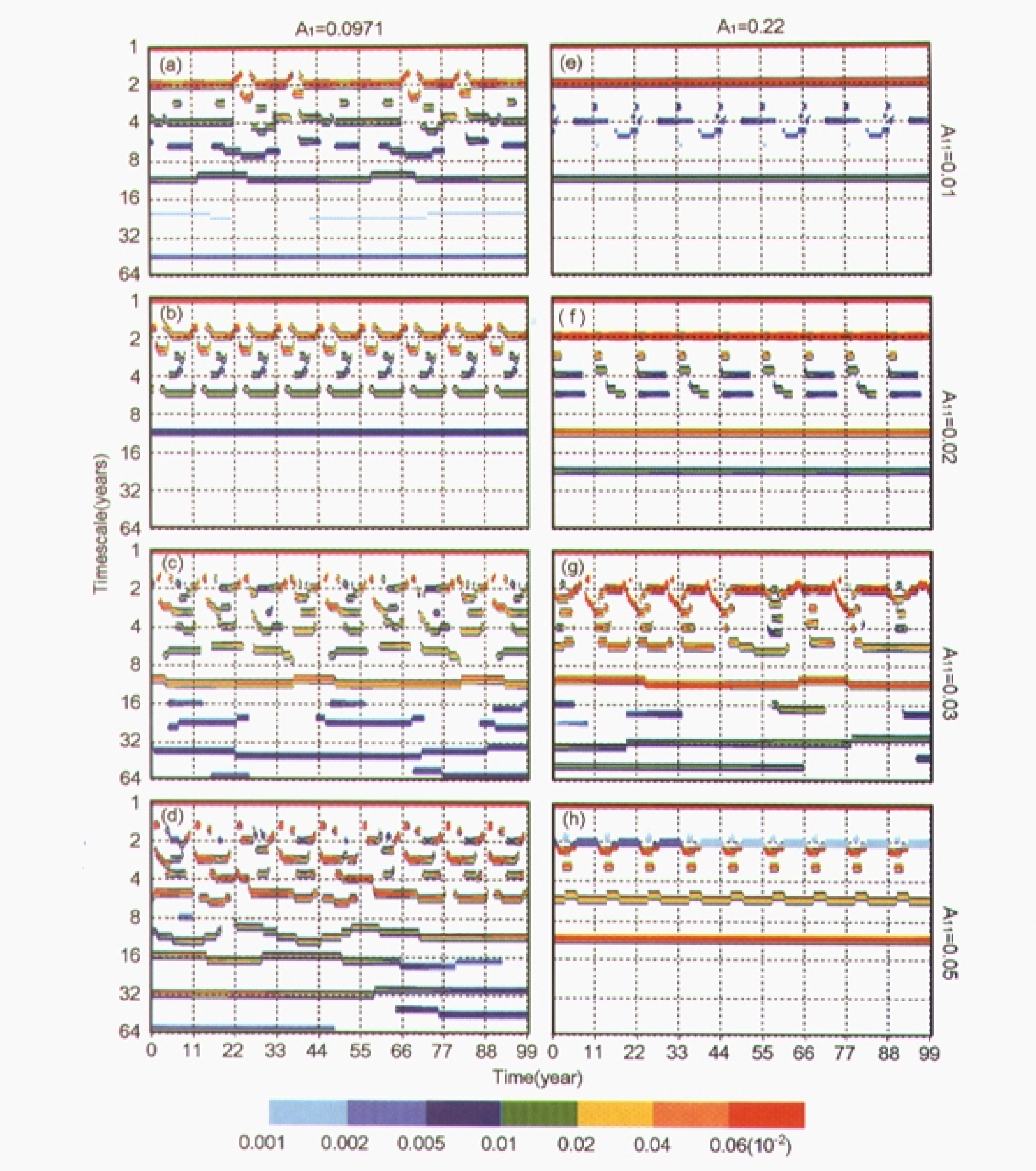

Fig. 1. The effect of change in the intensity of the external forcing on the responding timescales of the system. In each of the eight panels, Morlet wavelet amplitudes of separable components are shown in the time-timescale domain. There are two sets of experiments, each with a fixed seasonal forcing of $A_1=0.0971$ (left panels) or $A_1=0.22$ (right panels), as the intensity of the 11-yr solar modulation increases from the top to the bottom: $A_{11}=0.01$ in (a, e), $A_{11}=0.02$ in (b, f), $A_{11}=0.03$ in (c, g) and $A_{11}=0.05$ in (d, h). A uniform (non-uniform or broken) horizontal bar crossing the time domain for a given timescale represents a stationary (nonstationary) component on that timescale.

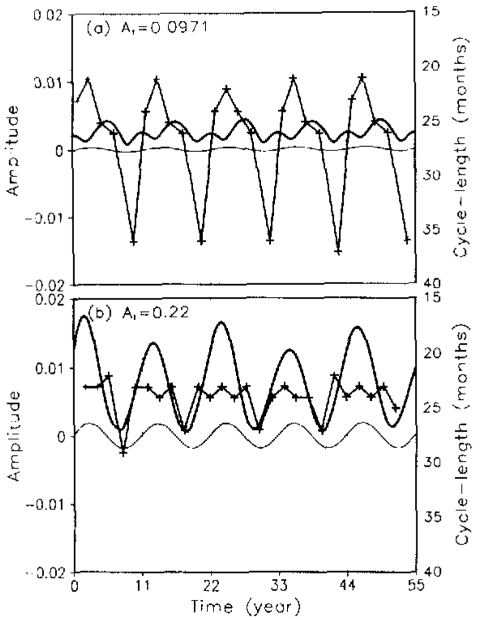

Fig. 2. The effect of change in the intensity of the seasonal forcing on cycle-length (thick lines) and intensity (lines with marks) of the resultant QBO when the solar modulation exists. The two cases of Fig. 1b and Fig. 1f are chosen with the same 11-yr modulation (A_{11}=0.02) but different intensities of the seasonal forcing: (a) A_1=0.0971, and (b) A_1=0.22. The amplitudes of the resultant QBO are calculated based on the Hilbert Transform in Matlab software package for the (20–36 months) band-passed time series. The cycle-length is calculated based on the length from a minimum to the next and plotted at the middle marked point. The vertical grid lines are where the minima of the 11-yr modulation are located. The responding 11-yr signals from the wavelet coefficients (thin lines) are also shown.

and its 5.5-yr harmonic. As shown in Fig. 1b, in the range of20 to 36 months, there are not only the 2-yr component and its sidebands, but also a very weak 3-yr component and its 2.8-yr sideband. Since all the components are amplitude-modulated and intensify alternately during the modulation cycles, both the cycle-length and the amplitude of the resultant QBO vary on both the 11-yr cycle and its 5.5-yr harmonic. Thus, this time series exhibits a vacillating QBO. The cycle-length and the amplitude of the resultant vacillating QBO are mainly determined by the intensity of the dominant components (Weng, 2001). In Fig. 2b (A_1 = 0.22), the cycle-length and the amplitude of the resultant QBO is modulated by both the 11-yr cycle and its 22-yr subharmonic. The amplitude of this resultant QBO varies with a large excursion, but the cycle-length has less of a range, than those in Fig. 2a. The mean cycle-length is very close to 24 months. It is in fact still a vacillating QBO because it contains QBO components. However, in practice, it may be considered as a vacillating BO.

The modulation of the cycle-length and the amplitude of a vacillating QBO signal on the 11-yr timescale along with its harmonics (5.5-yr and shorter) and/or subharmonics (22-, 33-, 44-years and longer) results in temporal variability of the QBO, which may explain why the mean cycle-length of a QBO signal may be different when data analyses are performed over different time intervals as found in previous studies (Trenberth, 1980; Quiroz, 1981; Baldwin et al., 2001).

The results shown in Fig. 2 also imply that whether a QB periodicity can really be observed in a climate parameter depends on the intensity of the seasonal forcing, when other parameters are fixed and the 11-yr solar modulation exists. The intensity of the seasonal forcing in a climate parameter depends on many geographical and dynamical factors such as the latitude, land-ocean contrast, air-sea-land interaction, topography, regional and remote influences, etc. Thus, different intensities of the seasonal forcing in different areas may result in different local QBO timescales. Different areas having largely in-phase or out-of-phase temporal variation in a climate parameter with similar QB periodicity and other timescales may form a teleconnection pattern.

Based on the analysis, we conclude that the internal processes in the climate system, though important to complete QBO cycles physically, can rarely result in the observed QB periodicity. When a periodic forcing exists, the nonlinear resonance of the system to the periodic forcing will transfer variability from the internal to the external timescales (Ghil, 1985). The observed QB periodicity is essentially forced by the seasonal cycle modulated by the 11-yr solar cycle, and contains multiple timescales resulting from complicated nonlinear interactions in the system. The dominant QBO components mainly determine the cycle-length and the amplitude of the resultant or the observed QBO signal that may change with time. Note that the dominant QBO timescales are dependent on the intensity of the seasonal forcing. As a result, two QBOs in different areas, where the intensities of the seasonal forcing are different, may not have a good linear correlation due to the lack of a coherent phase relationship between them. The areas where QBOs have similar dominant timescales and temporal behavior may be linked by a "teleconnection pattern". The real situation will be more complicated than what has been shown here, because the 11-yr solar cycle itself varies over longer timescales, and various climate parameters are also time-dependent and interact with each other. Hopefully, the results illustrated here by this simple forced dynamical system will enhance our understanding of the QB periodicity and its temporal and spatial variability observed in the complicated climate system.

Acknowledgments. The author is very thankful to Li Chongyin, Harry van Loon, Wang Shaowu, Ye Duzheng, and Zhu Baozhen for helpful discussions, and to an anonymous reviewer for constructive comments. This work was supported by the Director's Funds of LASG and the Innovative Funds of the Institute of Atmospheric Physics, Chinese Academy of Sciences.

REFERENCES

Baldwin, M. P., and Coauthors, 2001: The quasi-biennial oscillation. *Reviews of Geophysics*, **39**, 179–229.

Brier, G. W., 1978: The quasi-biennial oscillation and feedback processes in the atmosphere-ocean-earth system. *Mon. Wea. Rev.*, **106**, 938–946.

Chang, C. P., and T. Li, 2000: A theory for the tropical tropospheric biennial oscillation. *J. Atmos. Sci.*, **57**, 2209–2224.

Ghil, M., 1985: Theoretical climate dynamics: An introduction. *Turbulence and Predictability in Geophysical Fluid Dynamics*, M. Ghil et al., Eds., North-Holland Press, Amsterdam, 347–402.

Hamilton, K., 2002: On the quasi-decadal modulation of the stratospheric QBO period. *J. Climate*, **15**, 2562–2565.

Jin, F. -F., J. D. Neelin, and M. Ghil, 1994: El Niño on the Devil's staircase: Annual subharmonic steps to chaos. *Science*, **264**, 70–72.

Kim, K. M., and K. -M. Lau, 2001: Dynamics of monsoon-induced biennial variability in ENSO. *Geophys. Res. Lett.*, **28**, 315–318.

Kodera, K., 1993: The quasi-decadal modulation of the influence of the equatorial QBO on the north-polar stratospheric temperatures. *J. Geophys. Res.*, **98**, 7245–7250.

Labitzke, K., and H. van Loon, 1988: Association between the 11-year solar cycle, the QBO, and the atmosphere, I, The troposphere and stratosphere on the northern hemisphere winter. *J. Atmos. Terr. Phys.*, **50**, 197–206.

Landsberg, H. E., J. M. Mitchell, Jr., H. L. Crutcher, and F. T. Quinlan, 1963: Surface signs of the biennial atmospheric pulse. *Mon. Wea. Rev.*, **91**, 549–556.

Lau, K. -M., and H. -Y. Weng, 1995: Climate signal detection using wavelet transform: How to make a time series sing. *Bull. Amer. Meteor. Soc.*, **76**, 2391–2402.

Lau, K. -M., and H. -Y. Weng, 2001: Coherent modes of global SST and summer rainfall over China: An assessment of the regional impacts of the 1997-98 El Niño. *J. Climate*, **14**, 1295–1308.

Lean, J., 1991: Variations in the sun's radiative output. *Rev. Geophys.*, **29**, 505–535.

Li C. Y., Sun S. Q., and Mu M. Q., 2001: Origin of the TBO-Interaction between anomalous East-Asian winter monsoon and ENSO cycle. *Advances in Atmospheric Sciences*, **18**, 554–565.

Lindzen, R. S., and J. R. Holton, 1968: A theory of the quasi-biennial oscillation. *J. Atmos. Sci.*, **25**, 1095–1107.

Lorenz, E. N., 1964: The problem of deducing the climate from the governing equations. *Tellus*, **XVI**, 1–11.

May, R. M., 1976: Simple mathematic models with very complicated dynamics. *Nature*, **261**, 459 467.

Meehl, G. A., and J. Ablaster, 2002: The tropospheric biennial oscillation and Asian-Australian monsoon rainfall. *J. Climate*, **15**, 722–744.

Quiroz, R., 1981: Periodic modulation of the stratospheric quasi-biennial oscillation. *Mon. Wea. Rev.*, **109**, 665–674.

Rasmusson, G., X. Wang, and C. Ropelewski, 1990: The biennial component of ENSO variability. *J. Mar. Syst.*, 1, 71–90.

Salby, M., and P. Callaghan, 2000: Connection between the solar cycle and the QBO: The missing link. *J. Climate*, **13**, 2652–2662.

Sonett, C. P., C. R. Williams, and N.-A. Mner, 1992: The Fourier spectrum of Swedish riverine varves: evidence of sub-arctic quasi-biennial (QBO) oscillations. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* (*Global Planet. Change Sect.*), **98**, 57–65.

Trenberth, K., 1980: Atmospheric quasi-biennial oscillations. *Mon. Wea. Rev.*, **108**, 1370–1377.

Tziperman, E., M. A. Cane, and S. E. Zebiak, 1995: Irregularity and locking to the seasonal cycle in an ENSO prediction model as explained by the quasi-periodicity route to chaos. *J. Atmos. Sci.*, **52**, 293–306.

van Loon, H., and J. C. Rogers, 1978: The seesaw in winter temperature between Greenland and Northern Europe. Part I: General description. *Mon. Wea. Rev.*, **106**, 296–310.

Weng, H. -Y., and K. -M. Lau, 1994: Wavelets, period doubling, and time-frequency localization with application to organization of convection over the tropical western Pacific. *J. Atmos. Sci.*, **51**, 2523–2541.

Weng, H. -Y., 2001: A combined dynamic and kinematic view of amplitude vacillation in baroclinic flows. *Dynamics of Atmospheric and Oceanic Circulations and Climate*, the Institute of Atmospheric Physics, Chinese Academy of Sciences, Eds., China Meteorological Press, Beijing, 229–251.

Yasunari, T. , 1989: A possible link of the QBO between the stratosphere, troposphere and sea surface temperature in the Tropics. *J. Meteor. Soc. Japan*, **67**, 483–493.

太阳活动11年周期对气候系统中准两年振荡的影响

翁衡毅

摘　要

用一个有外强迫的、简单的动力系统研究气候系统中的准两年振荡(平均周期长度比两年稍长或稍短的准周期振荡)。结果显示，准两年周期性源于该系统对于受11年周期调制的季节强迫的非线性响应。当系统的非线性固定时，准两年震荡的周期长度和振幅随季节变化的强度和太阳活动11年周期变化的强度而变化。这可能是造成气候中准两年震荡的性质有时空变化的原因之一。

关键词：准两年震荡，季节强迫，太阳调制，非线性响应