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Conceptual model about the interaction between El Niño/ Southern Oscillation and Quasi-Biennial Oscillation in far west equatorial Pacific

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Abstract Interaction between the Quasi-Biennial Oscillation in far west equatorial Pacific (QBOWP) and the El Niño/Southern Oscillation (ENSO) is studied using a new conceptual model. In this conceptual model, the QBOWP effects on ENSO are achieved through two ways: (1) the oceanic Kelvin wave along equatorial Pacific, and (2) the Atmospheric Walker Circulation anomaly, while ENSO effects on QBOWP can be accomplished by the atmospheric Walker Circulation anomaly. Diagnosis analysis of the model results shows that the Atmospheric bridge (Walker circulation) plays a more important role in interaction between the ENSO and QBOWP than the oceanic bridge (oceanic Kelvin wave along equatorial Pacific); It is found that by the interaction of the ENSO and QBOWP, a free ENSO oscillation with 3—5 years period could be substituted by a oscillation with the quasi-biennial period, and the dominant period of SST anomaly and wind anomaly in the far west equatorial Pacific tends to be prolonged with enhanced ENSO forcing. Generally, the multi-period variability in the coupled Atmosphere-Ocean System in the Tropical Pacific can be achieved through the interaction between ENSO and QBOWP.

Keywords: El Niño/Southern Oscillation, Quasi-Biennial Oscillation, interaction, coupled system, Kelvin wave, Walker Circulation.

In the tropical Pacific region, El Niño/Southern Oscillation (ENSO) and the Quasi-Biennial Oscillation in far west equatorial Pacific (QBOWP) are two most prominent interannual variation phenomena. The former is characterized by coupled SST-wind variability of 2—7 years in the eastern equatorial Pacific while the latter by SST-wind variability of quasibiennial time scale in the far western equatorial Pacific. From the power spectra analysis of the observed SST (COADS SST from 1945 to 1993) in the eastern (150°W—90°W, 5°S—5°N) and the observed SST and zonal wind in the far western equatorial Pacific (120°—140°E, 0°—10°N) (Fig.1), in the eastern Pacific the period of SST interannual variability is 2—5 years, with the dominant peak at 3.6 years. In the western Pacific, on the other hand, at interannual time scales, the dominant peaks occur at about 2 and 5 years. The eastern Pacific SST variability is domi-

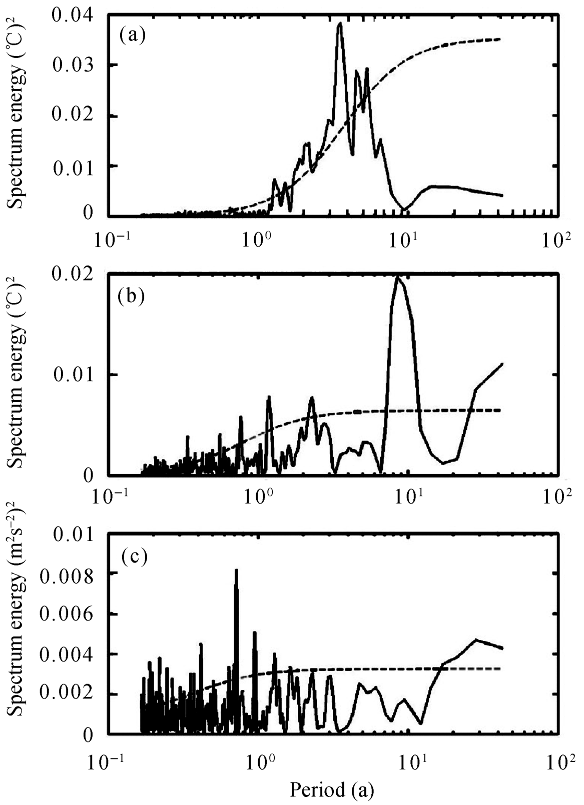

Fig. 1. Power spectrum of SST anomaly in east equatorial Pacific (150°W—90°W, 5°S—5°N) (a), the SST anomaly (b) and the zonal wind anomaly (c) in far west equatorial Pacific (120—140°E, 0—10°N) respectively based on COADS data (1945—1993).

nant with 4 years period, but also contains a significant 2-year peak, while in the western Pacific the SST and zonal wind also exhibit power at the dominant ENSO time scales (3—5 years) (Fig.1). Observations based on the SST along the equatorial Indian and Pacific ocean suggest significant eastward propagating wave of 2.3 years period, which is dominant among the eastward propagating waves at 3.0, 3.6, and 4 to 7 years periods, and standing waves of 3.6, 5—7 and 11 years periods[1,2]. This multi-period variability could be attributed to the nonlinear chaotic variability of ENSO itself [3,4] and the stochastic forcing effect[5]. QBOWP is the result of the local ocean-atmosphere interaction in far west equatorial Pacific[6], whether the interaction between QBOWP and ENSO is the main cause of the multi-period variability in tropical Pacific or not.

Observations have shown that ENSO has a significant impact on the interannual variability of the Asian monsoon[7−9]. On the other hand, monsoon also seems to affect characteristics of the ENSO[10−12]. Li and Hu[10] first put forth the possible excitement of El Niño by the anomalous strong winter east Asian monsoon and the related dynamical processes. Based on the "Delayed Oscillator" theory, Weisberg and Wang[13] further pointed out that the negative feedback mechanism of ENSO could be achieved by the local ocean-atmosphere interaction processes of the west Pacific without the reflection at the west boundary. Wang *et al.* [14] and Wang *et al.*[15] suggested that the surface wind in the western Pacific plays a critical role in the phase transition of ENSO cycle, which could excite eastward Kelvin wave and affect the SST anomaly in the eastern equatorial Pacific. Chang and Li[8] showed that the east-west Walker circulation anomaly associated with the anomalous monsoon heating is the dominant reason for the 2—3 months lag of the western Pacific SST behind the zonal wind anomalies. Lau and Wu[7] hypothesized that the quasi two-year variability of ENSO could be induced by the enhanced mosoon. Numerical experiments showed that the key mechanism of the quasi-biennial tendency during El Niño evolution is found to be the strong coupling of ENSO to monsoon wind forcing over the western Pacific[16].

Most previous studies are focused on the mechanism of ENSO[3,4,17] and QBOWP[6,8,18] separately, the mechanism of the interaction between ENSO and QBOWP has not been fully studied. As a first step here, a new conceptual model is constructed. This model consists of the conceptual ENSO model[17] and the QBOWP model[6]. The present new study is an attempt towards the understanding of the interaction between ENSO and QBOWP in a combined ENSO-QBOWP system. It is shown that QBOWP can impact ENSO by generating quasi-biennial variability in the eastern Pacific while ENSO can affect QBOWP by generating variability of ENSO period in the western Pacific SST, ENSO and QBOWP can coexist in the coupled ocean-atmosphere system in the tropical Pacific.

1 Conceptual model about the interaction between ENSO and QBOWP

The ENSO model is the delayed oscillator model of

Battisti and Hirst[17] (hereafter BH), linearized on the annual mean state, the perturbation SST equation is

$$\frac{\partial T}{\partial t}=-\bar{u}\cdot\nabla T-u\cdot\nabla\bar{T}-\delta\Delta(\bar{w})\frac{\partial T}{\partial z}$$

$$-\delta H(\bar{w})w\frac{\partial\bar{T}}{\partial z}-a_sT+Q\,. \quad (1)$$

Here, $Q=R/c_p\rho h$, R is the surface heat flux. ($\Delta(x)=x$ ($x>0$); $\Delta(x)=0$ ($x<0$); $H(x)=1$ ($x>0$); $H(x)=0$ ($x<0$), other variations are similar with BH).

In the eastern equatorial Pacific, the vertical temperature gradient is given by

$$\partial_z T=(T-T_s)/h, \quad (2)$$

where the subsurface temperature depends on the anomalous thermocline depth h as

$$T_s=a(\bar{h})h-e^*h^3, \quad (3)$$

with a and e^* being positive coefficients[11]. The anomalous upwelling in the eastern equatorial Pacific depends on the wind stress anomaly over the eastern equatorial Pacific

$$w=-\gamma_w\tau^x{}_E. \quad (4)$$

The anomalous eastern Pacific wind consists of two parts:

$$\tau^x{}_E=\beta T_E+p\tau^x{}_W\,. \quad (5)$$

The first part is due to local SST feedback, with T_E being the eastern Pacific SST anomaly and β being the coupling coefficient. The second part is related to the far western Pacific monsoon wind through the anomalous atmospheric Walker circulation, with p being an efficiency parameter. Using the sea surface wind from NCEP (1980—1999), the value of p is found to be about -0.6 (β=9.5×10^{-3} N m^{-2} ℃$^{-1}$), which means that both the anomalous wind stresses ($\tau^x{}_E$ and $\tau^x{}_W$) are opposite, because they are located on both sides of the anomalous convection center.

Averaging (1) in the eastern Pacific and using (2)—(5) lead to the equation for the eastern Pacific SST as

$$\frac{dT_E}{dt}=(K_A-\hat{K}+K_E\gamma_w\beta-a_s)\,T_E$$

$$+Kh+K_E\gamma_w p\tau_W^x-\hat{K}e^*h^3\,, \quad (6)$$

where h is the eastern Pacific equatorial thermocline anomaly; K, K_A, K_E and $\hat{K}$ are defined as in BH and the heat flux Q has been incorporated into the damping term a_sT.

Eastern equatorial Pacific thermocline anomaly is determined dynamically by both the local and remote effects as

$$h=h_{\text{Local}}+h_{\text{Remote}}, \quad (7a)$$

$$h_{\text{Local}}=a_L\tau^x{}_E,\ h_{\text{Remote}}=-a_W\tau^x{}_E(t-\tau)+a_H\tau^x{}_W(t-\tau_K). \quad (7b)$$

The remote response in (7b) has two parts. One is the response to an earlier eastern Pacific wind which returns back as a negative feedback to the eastern Pacific SST with a delay time τ (6—9 months), which is associated mainly with the equatorial Rossby wave. The other is the thermocline response to western Pacific zonal wind, which arrives at the eastern Pacific with a delay of the equatorial Kelvin wave time τ_K (2—3 months). For convenience here, we assume a_H= a_W in this paper, with the thermocline anomaly (7), the eastern Pacific SST equation (6) can be written as the delayed oscillator equation:

$$dT_E/dt = cT_E - bT_E(t-\tau) - nh^3$$

$$+p[c_EM-bM(t-\tau)]+b(a_H/a_W)M(t-\tau_K), \quad (8)$$

where $M=\tau^x{}_W/\beta$ is proportional to the zonal wind anomaly in the western Pacific. The parameters, following BH, are: $b=K\beta a_W$, $c_E=\beta(Ka_L+K_E\gamma_w)$, $c=c_E+K_A-\hat{K}-a_s$ and $n=\hat{K}e^*$. This equation represents the ENSO forced by the western Pacific monsoon wind through the oceanic (Kelvin wave) bridge and the atmospheric (Walker circulation) bridge. Typical parameter values are set the same standard case as in[11]: K=2.7×10^{-8} ℃ m^{-1} s^{-1}, K_E=2.5×10^{-2} ℃ m^{-1}, $\hat{K}$ = 1.8×10^{-7} s^{-1}, K_A=7.3×10^{-8} s^{-1}, a_L =750 m^{3}N^{-1}, a_W = 370 m^{3}N^{-1}, $a_s=9.1\times10^{-8}$ s^{-1}, τ=180 days, $\beta=9.5\times10^{-3}$ N m^{-2}℃$^{-1}$, γ_w=3.3×10^{-4} m^3 N^{-1}s^{-1}, e^*=3×10^{-5} ℃m^{-2}. The interaction coefficient μ_1 represents the QBOWP effect on the eastern Pacific ENSO through the oceanic bridge and μ_2 represents the QBOWP effect through the atmospheric bridge. Now, (8) is written as

$$dT_E/dt=cT_E-bT_E(t-\tau)-nh^3+\mu_2 p[c_EM$$

$$-bM(t-\tau)]+\mu_1 b(a_H/a_W)M(t-\tau_K)\,. \quad (9)$$

The QBOWP equation for the far western Pacific follows closely that of Clarke *et al.* (1998)[6]. The far western Pacific SST (T_W) equation is forced mainly by the wind-evaporation feedback as

$$\frac{dT_W}{dt}=-\gamma\frac{U}{S}u_W-\nu T_W^3\,, \quad (10)$$

where U and S are the climatological seasonal cycle of zonal wind and total wind speed separately. The far western Pacific wind anomaly is defermined by local SST anomaly and the Walker circulation anomaly depent on the zonal SST difference (zonal grads):

$$u_W = \lambda T_W(t-\tau_d) + \lambda_W(T_E - T_W). \quad (11)$$

The parameters λ =2.9 ms^{-1}K^{-1}, γ=2.2×10^{-7}Km^{-1} and τ_d =2 month are from Clarke *et al.* (1998)[6]. The model (11) recovers the equation for QBOWP of Clarke *et al.*[6] if $\lambda_W = 0$. Using

$$M = \alpha_M u_W / \beta, \quad (12)$$

and introducing a relative interaction parameter μ_3 that represents the impact of ENSO on QBOWP, (11) can be written as

$$u_W = \lambda T_W(t-\tau_d) + \mu_3\lambda_W(T_E - T_W). \quad (13)$$

Eqs. (9) and (10), (12) and (13) form our coupled ENSO-QBOWP system. Since previous studies[14,15] show that the effect of ENSO on sea surface wind in the far western Pacific is dominated by the local SST effect, we have the parameter range of $\mu_3\lambda_W << \lambda$. In present study, we take λ_W = 0.17 ms^{-1} K^{-1} and therefore the effect of this term is determined by μ_3. Its-standard deviation is estimated at about 0.5 for the tropical ocean-atmosphere coupled system using COADS data (recent 50 years). In this paper, μ_1, μ_2 and μ_3 are non-dimensional paramaters and range from 0 to 1. These three parameters represent the linkness effect of the two idealized models. If all of them are set at zero, then the QBOWP of the far west Pacific and the ENSO of the central and east Pacific are totally decoupled. If all are set at 1, then the two systems are unseparated. Then we can let μ_1, μ_2 and μ_3 vary between 0 and 1 to represent the different interactions between ENSO and QBOWP.

2 Interaction between ENSO and QBOWP

When the interaction coefficients $\mu_1 = \mu_2 = \mu_3 = 0$ in eqs. (9) and (10), ENSO and QBOWP are decoupled as the standard free ENSO and QBOWP (Fig. 2). The free ENSO has an amplitude of 3.85℃ and a period of 3.2 years[11], while the free QBOWP has an amplitude of 0.35℃ and a period of about 2 years[6].

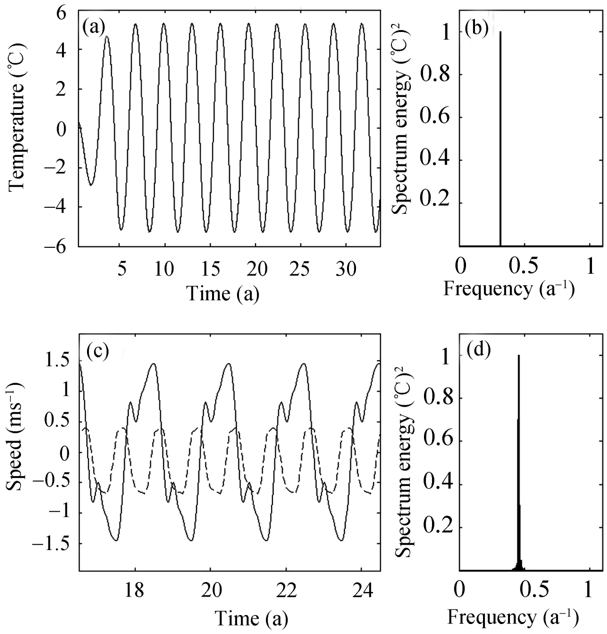

Fig. 2. Without interaction between ENSO and QBOWP (μ_1= μ_2=μ_3=0). (a) Time series of T_e during first 34 years, (b) power spectrum of T_e during 200 years; (c) time series of zonal sea surface wind stress in the far west equatorial Pacific τ^x_w (solid) during 16.5th—24.5th year and the *U/S* (dashed) and (d) power spectrum of T_w for T_e, τ^x_w and T_w are 200-year time series of the conceptual models (9) and (10).

2.1 *QBOWP impact on ENSO*

The one-way impact of QBOWP on ENSO can be studied in our conceptual model by shutting off the feedback of ENSO on QBOWP with μ_3=0, such that the QBOWP remains the same as the free QBOWP in Fig. 2(c),(d). and it shows that QBOWP affects ENSO significantly in both amplitude and period (Fig. 3). The left column shows the amplitude of ENSO (calculated as the standard deviation of T_e) as a function of an enhanced oceanic (Kelvin wave) bridge effect (μ_1), for several given intensity of the atmospheric (Walker circulation) bridge (μ_2). The right column shows the variation of the frequencies of T_e with μ_1 for different μ_2. In the absence of the atmospheric bridge (μ_2= 0), an intensification of the QBOWP impact on the eastern Pacific through the oceanic bridge (increasing μ_1) suppresses the amplitude of T_e rapidly. This reminds of the ENSO suppression by a periodic forcing in [11] and [12], except that now the external forcing is the QBOWP, rather than the annual

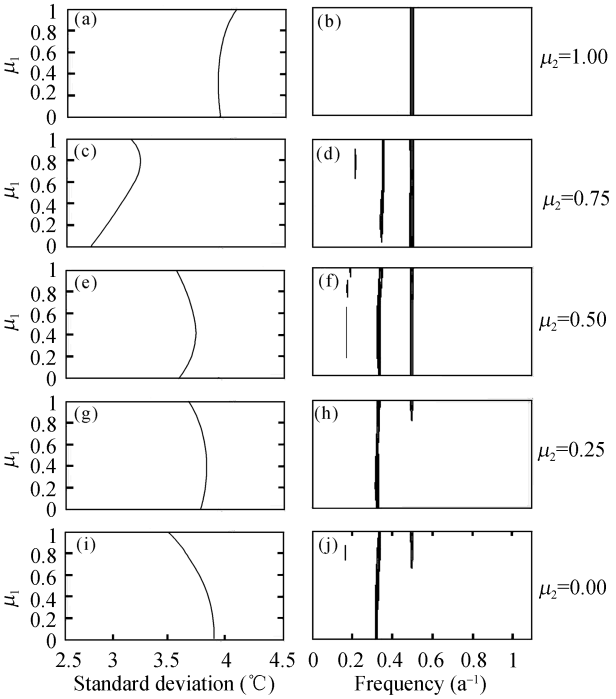

Fig. 3. Dependence of (left) amplitude and (right) frequency of T_e on μ_1 and μ_2, when μ_3=0. T_e is 200-year time series of the conceptual models (9) and (10). The right column shows the power spectrum, now as contours of the standard energy spectral density on the frequency-μ_1 plane. Each panel shows the variation of the amplitude and dominant frequencies of T_e with μ_1 for different μ_2.

monsoon. For weak QBOWP impact, T_e is dominated by the period of the free ENSO (f = 0.32 a^{-1}). With further enhanced QBOWP impact, QBOWP (f = 0.5 a^{-1}) and the subharmonic frequency of QBOWP and ENSO (f = 0.18 a^{-1}) emerge, the intensity of T_E first decreases and then increases with limited amplitude (μ_1, μ_2<1), which means that lower frequency signals could be induced when ENSO is forced by high frequency signals. Free ENSO frequency f_1, forcing QBOWP frequency f_2 and the subharmonic QBOWP frequency f_3 fulfil the relation below:

$$f_1=(f_2+f_3)/2. \tag{14}$$

When the QBOWP effect is strong enough through the atmospheric bridge (μ_2=1), the original free ENSO oscillation is completely suppressed and T_e is dominated by the QBOWP.

The message from Fig. 3 is: enhanced QBOWP forcing tends to change the climate variability from a free ENSO oscillation to a forced biennial oscillation in the eastern Pacific, increasing the biennial variability significantly at the expense of the variability of 3—5 years. As a result, both ENSO and biennial oscillation can occur in the eastern Pacific with other new oscillation signals. The Walker circulation appears to play an important role for the monsoon to affect ENSO.

2.2 *ENSO impact on QBOWP*

The one-way impact of ENSO on QBOWP can be studied by setting $\mu_1 = \mu_2$ =0 in (9), which suppresses the feedback of QBOWP on ENSO such that SST anomaly in the east Pacific remains as the free ENSO in Fig. 2(a), (b). The ENSO impact on QBOWP through an enhanced effect of the atmospheric Walker circulation can be seen in Fig. 4 by increasing μ_3 in (13), the impact of the ENSO is seen in both amplitude (STD) and period of T_w. For small ENSO impact (small μ_3), T_w is dominated by that of the biennial oscillation and the amplitude weakens from 0.33℃ to 0.23℃ with an increase of μ_3, which reflects a suppression of QBOWP by the external forcing of

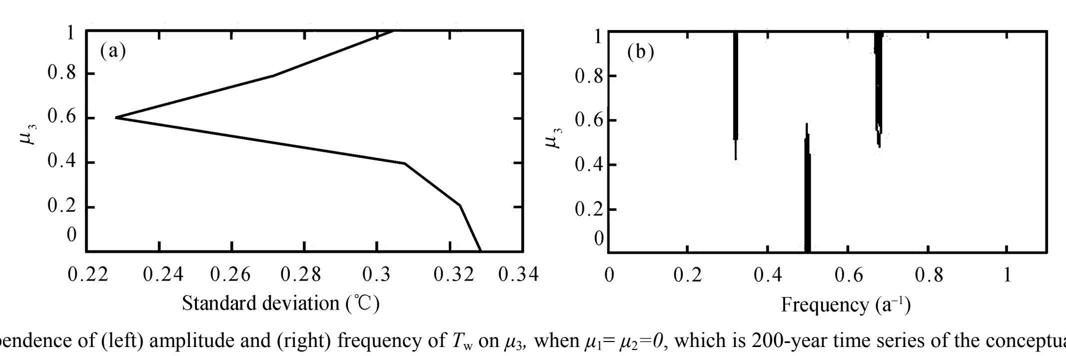

Fig. 4. Dependence of (left) amplitude and (right) frequency of T_w on μ_3, when μ_1= μ_2=0, which is 200-year time series of the conceptual models (9) and (10). The right column shows the power spectrum, now as contours of standard energy spectral density on the frequency-μ_3 plane.

ENSO. With further enhanced ENSO impact (μ_3 >0.6), the QBOWP vanishes and T_w variability is dominated by the variability of ENSO (~3 a). In addition, a superharmonic signal (~1.5 years) emerges as the secondary variability. Generally, enhanced ENSO forcing tends to change the variability of the SST and wind in the western Pacific from the dominant QBOWP to a forced ENSO through the anomalous Walker circulation. Higher frequency oscillation (f_3) could be excited when the QBOWP system (f_1) is modulated by the low frequency ENSO (f_2) forcing, three frequencies alse fulfil relation (14).

2.3 Interactive ENSO-QBOWP system

Fig. 5 shows the variation of power spectrum of T_e and T_w with μ_3 for μ_1 =0.8, and μ_2 = 0, 0.25, 0.5, 0.75 and 1 respectively. The left and right columns show the power spectra of the western Pacific SST (T_w) and eastern Pacific SST (T_e), and their variability with μ_3 respectively. For μ_1 =0.8 and μ_2 =0, an increasing ENSO impact on the western Pacific leads to the weakening of the QBOWP and as a result, the ENSO and the superharmonic signal concur after μ_3 exceeds 0.5 (Fig.5(i)), which is similar to the results in Fig. 4(b), and the frequencies of the forcing wave and harmonic wave all fulfil eq. (14). Interestingly, by comparing Fig. 4(b) with Fig. 3(b), because the interaction of both sysyerms coexists, the frequency of the forcing wave is lowered and that of the harmonic wave becomes higher in the far west Pacific with the increment of μ_3. When μ_3 surpasses 0.5, the oscillation period of the SST in the eastern Pacific is prolonged to 5 years due to the nonlinear interaction between ENSO and QBOWP. The feedback of zonal wind in the west equatorial Pacific on the eastern Pacific through the Walker circulation, however, leads to a slightly shortened ENSO period with increases of μ_2 (Fig.5(j), (h), (f), (d), (b)). These features remain qualitatively similar with the additional monsoon impact on the eastern Pacific[11,12]. If the QBOWP feedback by Walker circulation is strong enough (μ_2 >0.75), the SST anomaly in both western and eastern Pacific will be dominated by the 2-year variability (Fig.5(a)—(d)).

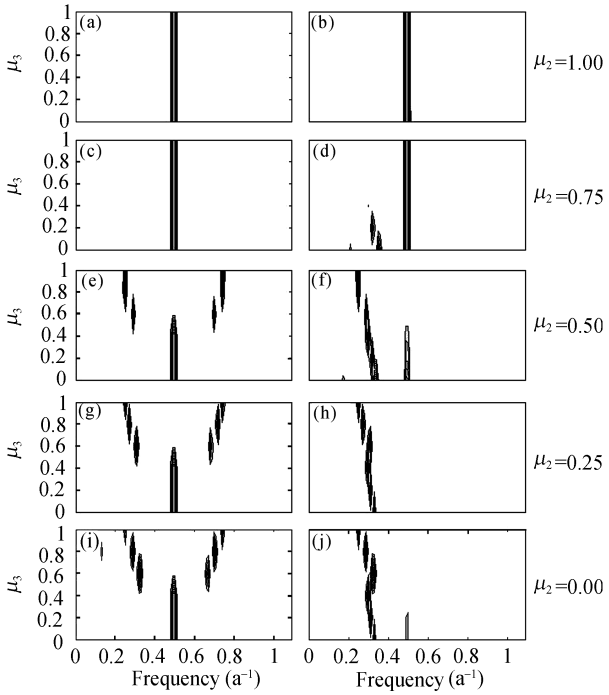

Fig. 5. Dependence of frequency of T_w (left) and T_e (right) on μ_3 and μ_2, when μ_1=0.8, T_w and T_e are both 200-year time series of the conceptual model, (9) and (10). In each panel the power spectrum, now as contours of standard energy spectral density on the frequency-μ_3 plane. Each panel shows the variation of the amplitude and dominant frequencies of T_e with μ_3 for different μ_2.

For μ_2=0.5, QBOWP and ENSO can coexist. Quasi-2 years and 3—4 years period oscillations concur in the easern Pacific with μ_3<0.5 (Fig. 5(f)). When μ_3>0.7, now, the dominant variability with 3—4 years period requires a stronger ENSO impact in the western Pacific, (Fig. 5(e)). A power spectra peak emerges with about two-year period in the eastern Pacific (Fig. 5(f)). One example that may be relevant to the present tropical Pacific climate is shown in Fig. 6, with μ_1 = 0.8, $\mu_2 = \mu_3 = 0.5$. In the ENSO-QBOWP coupled system, it is seen that the eastern Pacific is dominated by two major variability, ENSO (f is about 3.2 a^{-1}) and the biennial oscillation (f is about 0.5 a^{-1}); in addition, a weak subharmonic oscillation with about 5 years period (f = 0.18 cycle/a) can be detected too (Fig. 6(a), (d)). These features can also be seen clearly in the time series of eastern Pacific SST anomaly (dash-dot line in Fig. 6(a)), which shows a clear signal of biennial oscillation in addition to ENSO variability. The western Pacific SST anomaly is still dominated by the biennial

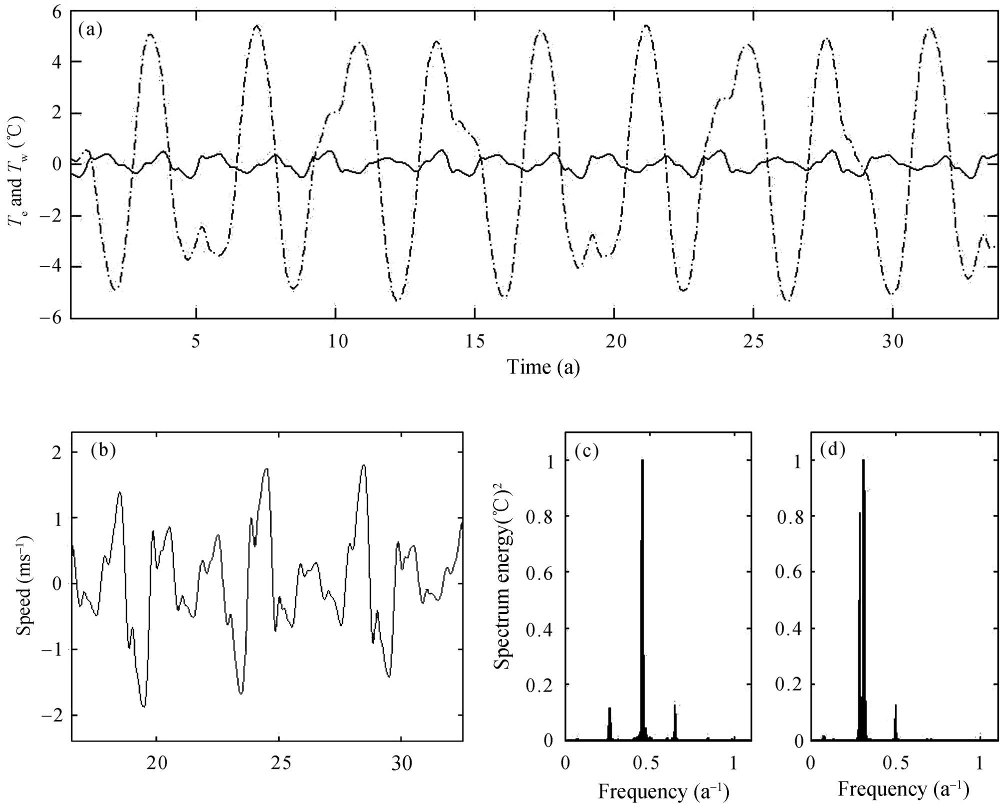

Fig. 6. (a) Time series of T_e (line with point) and T_w (solid) during the first year to the 34th year, (b) time series of τ^x_W during the 16th to the 34th year, (c) power spectrum of T_w and (d) power spectrum of T_e. The T_e and T_w are the 200-year time series of the conceptual models (9) and (10), including the interaction between ENSO and QBOWP (μ=1.0, μ_1=0.8, $\mu_2=\mu_3$=0.5).

oscillation, with weaker power spectra peaks emerging at the period with 3.6 a and a superharmonic oscillation(Fig. 6(c)). This dominant signal with about 0.5 a^{-1} in western Pacific SST anomaly (T_w) is also seen clearly in the time series in Fig. 6(a) (solid line). The time series of the far western Pacific wind τ^x_W (Fig. 6 (b)), however, has a much stronger component of variability with 3-year period. This occurs because, as shown in (13), the zonal wind depends on SST not only locally in the western Pacific, but also remotely in the eastern Pacific. The latter is part of the atmospheric Walker circulation effect that enables ENSO to affect western Pacific zonal wind.

This example shows that multi-period climate variability in Pacific Coupled Atmosphere-Ocean System can be induced by the interaction between ENSO and monsoon. Although the model is highly idealized, it still has implications on the present climate variability. Our study suggests that the interaction between QBOWP and ENSO may also play a role in generating this rich spectrum of tropical climate variability.

3 Summary

A conceptual model is constructed by combining the delayed oscillator ENSO model in the eastern Pacific[17] with the far western Pacific QBOWP model[6]. The QBOWP impact on ENSO is accomplished by both the oceanic Kelvin wave effect and the atmospheric Walker circulation, while ENSO affects QBOWP through the atmospheric Walker circulation. An enhanced interaction between QBOWP and ENSO tends to change the climate variability from a free ENSO oscillation to a forced biennial oscillation in the easterm Pacific, with the suppression of variability of 3—5 years periods and the enhancement of the biennial variability in the eastern Pacific; an enhanced ENSO forcing on the western Pacific also changes the

QBOWP variability into a forced variability with 3－5 years period in the far west Pacific, suppressing variability of the 2-year period, while increasing variability of ENSO time scales in the west Pacific. In the fully coupled ENSO–QBOWP system, the ENSO variability and QBOWP variability can coexist in both the eastern and western Pacific. Therefore, we suggest that the interaction between ENSO and QBOWP may contribute to the observed present climate variability. Because our model is highly idealized, more realistic models are needed to further understand the role of monsoon-ENSO interaction and its impact on tropical climate variability.

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