9.7 A Theory for the Prevailing Easterlies and Eastward-Shoaling Sloped Thermocline over Equatorial Pacific and the Accompanying ENSO Variability

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1. Introduction

The equatorial ocean-atmosphere climate system is characterized with a strongly west-east asymmetric time mean state accompanied with which is an El Niño-Southern Oscillation (ENSO) variability with a dominant time scale of 3-4 years. The question we attempt to address in this paper is: *In the absence of an external pre-existing west-east asymmetry of any kinds, can the coupled equatorial ocean-atmosphere dynamics alone give rise spontaneously to both a realistic west-east asymmetric mean state and an ENSO-like interannual variability as in observation*? In other word, we wish to explain the observed west-east asymmetric mean state and ENSO variability over the equatorial Pacific basin without taking advantage of "knowing" any factors that could directly attribute to a west-east asymmetry within the basin.

2. Model

The coupled equatorial Pacific ocean-atmosphere model used in this study is

$$\frac{\partial u}{\partial t} - \beta y v + g'\frac{\partial h}{\partial x} = \frac{\tau}{\rho H}\ , \qquad (1.a)$$

$$\beta y v + g'\frac{\partial h}{\partial y} = 0\,, \qquad (1.b)$$

$$\frac{\partial h}{\partial t} + H\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0\,, \qquad (1.c)$$

$$\int_{Y_s}^{Y_n} u\,dy = 0 \text{ at } x = 0,\ u = 0 \text{ at } x = L.$$

$$\tau = \tau_0 \sin\left(\frac{\pi x}{L}\right)\exp\left(-\left(\frac{y}{Y}\right)^2\right), \qquad (2)$$

$$\tau_0 = -\alpha\frac{A_0}{L}\left(T_{west}(t) - T_{east}(t)\right), \qquad (3)$$

$$\frac{\partial T_{bdn}}{\partial t} = -2\delta\tau_0[T_{bdn} - T_{S0} - (T_0 - T_{S0})]\times \tanh\left(\frac{h_{bdn}}{H^*}\right) \mathcal{H}(-\tau_0) - \mu(T_{bdn} - T_0) = 0, \qquad (4)$$

where u and v are the depth-averaged zonal and meridional currents of upper layer ocean; h is the departure thickness of upper layer ocean from a constant mean depth H; τ is the zonal wind stress to be determined from the atmospheric model (3). In (4), T is the sea suface temperature and the subscript "bdn" stands for either "west" or "east". Heaviside function $\mathcal{H}(-\tau_0)$ is defined as $\mathcal{H}(-\tau_0) = 1$ if $\tau_0 < 0$ and $\mathcal{H}(-\tau_0) = 0$ if $\tau_0 > 0$. The term associated with Heaviside function represents the SST change due to Ekman upwelling dynamics.

Eqs. (1)-(4) form a close set of equations for the coupled equatorial Pacific ocean-atmosphere system. Obviously, the zonally leveled thermocline with no current plus $T_{west} = T_{east} = T_0$ and windless atmosphere is an equilibrium solution (the trivial solution).

Eq. (1) is solved numerically with a grid size of 2° (longitude) by 0.5° (latitude). The model domain is rectangular and extends from 124° E to 80° W (L = 17316 km) and from Y_s = 28.75° S to Y_n = 28.75° N. The numerical values of the model parameters are: g` = 0.003g (g is the Earth gravity equal to 9.8 m/sec.^{2}), H = 145m, $\beta = 2.28\times10^{-11}$ sec.$^{-1}$. With these values of the model parameters, the Kelvin wave speed is about 2.07 m/sec. and the oceanic Rossby deformation radius is about 300 km.

There are five parameters in (4). They are T_0 , T_{S0}, δ , μ , and H*. T_0 is the zonally uniform equilibrium temperature at the equator in the absence of any dynamics. T_{S0} is the reference subsurface layer temperature. The standard numerical values of the five parameters and the parameter Y used in (2) are given in Table 1.

Table 1. Model Parameter Setting

Parameters	Values
δ	$\frac{10}{3months \times dyne/cm^2}$
μ	1/(50 months)
T_0 and T_{S0}	30°C and 25°C
H*	145 m (= H)
A_0/L	0.2 $dyne/cm^2/°C$
Y	7.5 latitudes

The dimensional portion of the coupling coefficient A_0 /L has a preset value (given in Table 1). We will scan the non-dimensional coupling coefficient, α, from 0 to 1. This would enable us to examine how the zonally symmetric state (the trivial solution) evolves towards a west-east asymmetric one as the coupling strengthens. Physically, the coupling coefficient in the coupled system (1)-(4) measures the efficiency of the atmospheric engine fueled by the basin-wide SST difference. Therefore, from the observation, we should be able to estimate a priori the "appropriate" value of the coupling coefficient α at which the coupled system (1)-(4) would produce a realistic climatology and an ENSO-like oscillation. From the observation, the mean wind stress is 0.55 $dyne/cm^2$ for a mean basin-wide SST difference of 4.2°C. This yields $\alpha = 0.65$.

3. Results

Fig.1 depicts the evolution of the behaviors of this coupled system at the representative values of the coupling coefficient α. When air-sea interaction is disabled ($\alpha = 0$), the basin-wide thermocline depth difference (solid curve) displays a damped oscillation with a period of about 1 year, an uncoupled time scale of equatorial oceanic waves over the Pacific basin. For $0 < \alpha \leq 0.57$, the ocean-atmosphere system becomes uncoupled at a large time due to the diminishment of basin-wide SST difference. This implies that the zonally symmetric state is a stable equilibrium solution of the coupled system for $\alpha \leq 0.57$. Nevertheless, the coupled dynamics results in a systematic change to the ocean system, namely that the time scale of the coupled adjustment (the oscillation before the basin-wide SST dying out) tends to increase with the coupling coefficient. It follows that the periods of the coupled system for α=0, 0.3,and 0.5 are approximately equal to 1, 1.9, and 3.5 years, respectively. As α approaches 0.58, the period tends to become longer and longer (approximately up to 17 years as revealed in our numerical solution). The zonally symmetric state, however, is still the stable state of the coupled system.

A further increase of α ($\alpha \geq 0.58$) leads to an instability of the zonally symmetric state and gives birth to a new equilibrium state at which the thermocline (SST) is deep (warm) in the west and shallow (cold) in the east, and the atmosphere has a prevailing easterly at the equator. The strength of the coupled climatology, measured by the magnitude of basin-wide thermocline depth (SST) difference and the mean wind stress, increases with the coupling coefficient. For $\alpha = 0.58$, the oscillation about the coupled climate state is a damped one with a period of about 17 years. A slightly larger α ($\alpha = 0.62$) gives rise to a self-sustained finite-amplitude oscillation about the coupled climate with a period of 4.2 year, which is much shorter than the case when $\alpha = 0.58$. As α continues to increases, the strength of the self-generated climate state amplifies and the accompanied self-sustained oscillation period becomes shorter.

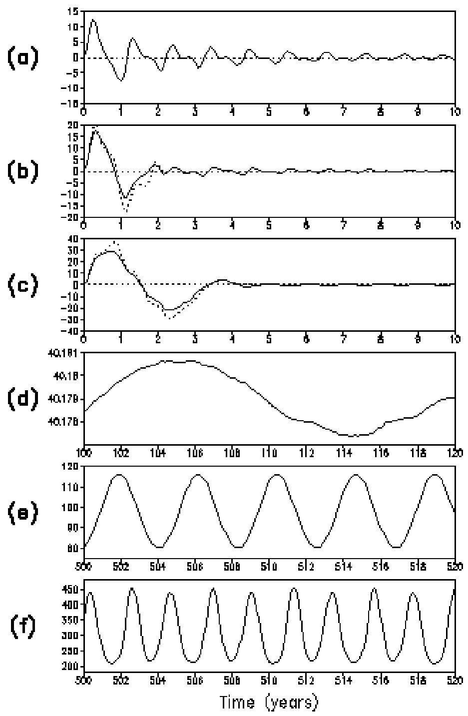

Fig. 1 Panels (a)-(f) correspond to the fully coupled solution of (1)-(4) with α = 0.0, 0.3, 0.5, 0.58, 0.62, and 1.0, respectively. The solid curve is time series of (h_{west} - h_{east}) in unit of meters. The dotted curve in (b) and (c) is time series of (T_{west} — T_{east}) in unit of (1/30) °C.

Fig. 2 summarizes the solutions of the coupled system as a function of the coupling coefficient. As illustrated in Fig. 1, the zonally symmetric state of the coupled system is stable till α reaches a critical value ($\alpha = \alpha_0 \approx 0.575$). For $\alpha \leq \alpha_0$, the oscillation period (the curve with open circles) increases with the coupling coefficient. When $\alpha > \alpha_0$, the zonally symmetric state is unstable, resulting in a new equilibrium state that has a zonally sloped thermocline. The thermocline depth difference across the basin (the curve with solid circles) increases as coupling coefficient increases. In contrast to the cases of $\alpha \leq \alpha_0$, the oscillation period now decreases from the peak value at $\alpha = \alpha_0$, as the coupling coefficient increases. There is additional critical value of α ($\alpha = \alpha_1 \approx 0.61$), above which the oscillation is no longer damped but self-sustained (indicated by solid portion of the curves). The amplitude of the self-sustained oscillation (the thin curve), measured by the difference between the maximum and the minimum of (T_{west} — T_{east}), is about 4°C and changes little with the coupling coefficient soon after α exceeds α_1.

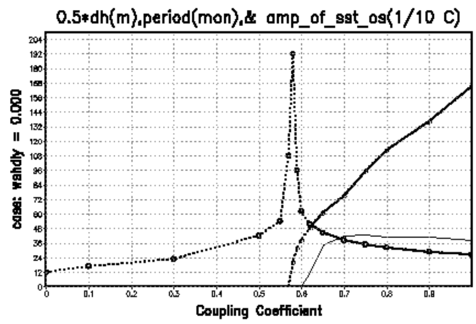

Fig. 2 A summary diagram of the fully coupled model solutions. Abscissa is coupling coefficient. The curve with open circles is the oscillation period in unit of months. The thick curve with solid circles is the time mean of (h_{west} - h_{east}) /2 in unit of meters. The thin curve is amplitude of self-sustained oscillations, measured by the difference between maximum and minimum of (T_{west} — T_{east}) in unit of 0.1 °C. The dotted portion of the curves corresponds to damped oscillations and the solid portion represents self-sustained oscillations.

When α in the neighborhood of 0.65, the fully coupled model indeed produces a realistic mean state and ENSO-like oscillation. As shown in Fig. 3, the basin-wide thermocline depth (SST) difference is 116 meters (4.2°C) and the westward wind stress at the central Pacific basin is 0.54 dyne/cm^2. This mean climate state is accompanied by a self-sustained oscillation with a primary period of 3.7 years. The SST at the west oscillates between 27.5°C and 28.5°C whereas the SST at the east oscillates in the range from 25.2°C and 22.5°C. All of these features arise spontaneously from the coupled instability without a zonally asymmetric external

The power spectral analysis reveals that the self-sustained oscillation is not a simple harmonic oscillation due to the nonlinearity (not shown). In addition to the primary harmonics that has a period of 3.7 years, there are subharmonics with periods equal to 1.85, 1.23, 0.925 years, and so on.

4. The proposed theory

The results presented above lead to a mechanism that explains both why the equatorial Pacific climate state is zonally asymmetric and why the dominant oscillation about this climate state, such as ENSO, has a much lengthened time scale compared to that of the free equatorial oceanic waves. ***The essence of the newly proposed mechanism is that the basin-wide coupling of the equatorial ocean-atmosphere system effectively acts to reduce the net restoring forcing (or increase the momentum inertial) for the equatorial oceanic waves traveling within the equatorial ocean basin.*** As a result, the coupled oceanic waves travel more slowly due to this reduction of the restoring forcing.

When the coupling strength reaches a critical value, the coupled system becomes unstable at which the theoretical limit of the traveling time scale would be infinite without nonlinearity. Due to the nonlinearity of the coupled system, this primary air-sea interaction instability leads to one of two possible zonally asymmetric mean states via a pitch-fork bifurcation. The direction of the observable zonal asymmetry is dictated by the equatorial Ekman dynamics. As a result, only one of the two possible mean states is observed, namely, the atmosphere has a prevailing easterly and the ocean basin has a deep-in-west/shallow-in-east thermocline with a warm-west/cold-east sea surface temperature. The ENSO variability is an integral by-product of the coupled process. The much lengthened time scale of ENSO comes from two sources: (1) longer traveling time scale of the equatorial oceanic waves due to a reduction of effective restoring forcing in the coupled system and (2) a naturally evoked delayed-oscillator mechanism associated with the birth of the zonally asymmetric climate mean state. The delayed oscillator mechanism is also responsible for making the oscillation self-sustainable. The change of the oscillation time scale as a function of the coupling coefficient (i.e., Fig. 2) can be independently verified with an analytic solution (not shown here, but will be presented in the conference).

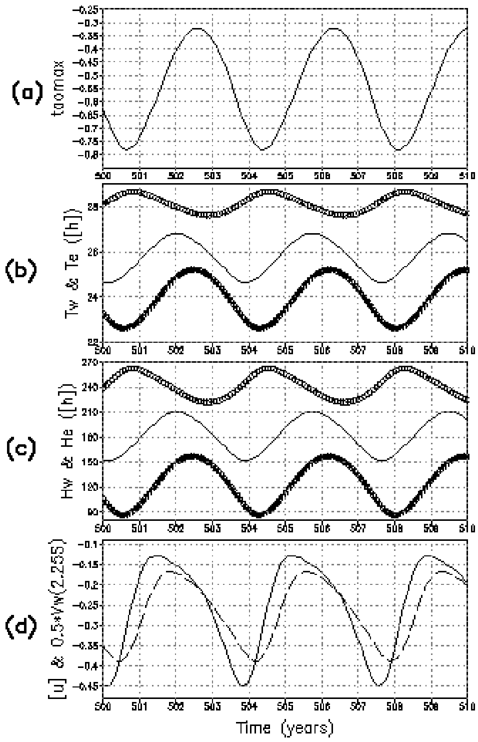

Fig. 3 Time series derived from the fully coupled model solution for $\alpha = 0.65$. Panel (a): wind stress at central Pacific basin (dyne/cm^2); Panel (b): SST (°C) in the western (open circles) and eastern (solid circles) basins, and zonal mean thermocline depth (thin curve; its scale is omitted for brevity); Panel (c): thermocline depth (meters) in the western (open circles), in the eastern (solid circles) basins, and the zonal mean thermocline depth (thin curve, scale omitted); Panel (d): zonal mean zonal current at the equator (solid) and the western boundary meridional current at 2.25°S (dashed) in unit of m/sec..