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COLLECTIVE AND COMPETITIVE ROLES OF THERMOCLINE AND ZONAL ADVECTIVE FEEDBACKS IN THE ENSO MODE

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1. INTRODUCTION

Established succinct conceptual models (Battisti and Hirst 1989; Suarez and Schopf 1988; Jin1997) for ENSO emphasize the role of the thermocline feedback (vertical advection of anomalous subsurface temperature by mean upwelling). However, the recent observation indicated that the zonal advective feedback (zonal advection of mean SST by anomalous current) is important as much as the thermocline feedback. This even led to that ENSO might be understood by focusing on the zonal advective feedback alone (Picaut et al. 1997). Recently, it was found that thermocline feedback and the zonal advective feedback indeed both important for the growth and phase transition of ENSO, and both feedbacks are closely related and can be naturally combined into the recharge paradigm for ENSO (An et al. 1999; Jin and An 1999).

2. A TWO-STRIP CZ-TYPE MODEL

From the equatorial β-plane shallow-water model, Jin (1997) derived the ocean-dynamics equations for h_e in the equatorial strip (y=0) and h_n in the off-equator strip centered at y_n :

$$(\partial_t + \varepsilon_m)(h_e-h_n) + \partial_x h_e = \tau_{xe},$$
$$(\partial_t + \varepsilon_m)h_n - \partial_x h_n / y_n^2 = \partial_y(\tau_x/y)|_{y=yn.} \qquad (1)$$

where τ_{xe} is the wind stress anomaly evaluated in the equatorial strip. The first equation describes the Kelvin wave signal along the equator with an inclusion of the effect of Rossby waves because h_n is the thermocline depth associated with Rossby-wave signals in the off-equatorial strip.

The change of equatorial SST is described by the following equation linearized about an upwelling climate state and the zonal gradient of climatological mean SST:

$$\partial_t T = -\varepsilon_T T + \gamma(x)h + a(x)u \qquad (2)$$

Where each term on the right-hand side of (2) represents a collective damping, the thermocline feedback, and the zonal advective feedback, respectively. Other anomalous advection terms are ignored throughout this paper for the sake of simplicity.

The zonal wind-stress anomaly based on the Gill-type response to SST anomaly is expressed as

$$\tau_{xe} = \mu A(T_e,x) \qquad (3)$$

$A(T_e,x)$ can be determined based on either the Gill-type model dynamics (e.g., Jin and Neelin 1993; Neelin and Jin 1993) or through an empirical relation of the equatorial wind stress and SST anomaly (An and Jin 2001).

By considering the two boxes (eastern and western) in the tropical Pacific and using the equations (1) to (3), one reduces the two-strip model to exactly the same form of the conceptual recharge oscillator model of Jin and An (1999) (Details in An and Jin (2001)).

$$\partial_t h_W = -rh_W - \alpha b T_{E,}$$
$$\partial_t T_E = (-c+(b\gamma+A_1 a_E))T_E + (\gamma+A_2 a_E)h \qquad (4)$$

Through systematic and reasonable simplification, thus, the conceptual model in Jin and An (1999) was obtained from the dynamic framework of a Cane-Zebiak-type coupled model (Cane and Zebiak 1985). Equation (4) clearly demonstrates that the zonal advective feedback indicated by the a_E plays a similar role as the thermocline feedback indicated by the γ.

3. NUMERICAL SOLUTION

To examine changes in the leading modes according to various feedback processes, we compared three cases: the thermocline-feedback alone ($a(x)=0$), the advective-feedback alone ($\gamma(x)=0$), and the two-feedback combined. In the case of the thermocline feedback alone (Fig. 1a), the nonoscillatory-damped SST and oceanic adjustment modes coexist in the low coupling regime, and the decay rate of the SST mode is effectively reduced by increasing μ; this damped SST mode eventually merges with the damped nonoscillatory ocean adjustment mode to produce a *mixed oscillatory mode*. On the other hand, the eigenmode for the zonal advective feedback alone case is related to the gravest ocean basin mode (Fig. 1b). The growth rate of this damped oscillatory ocean adjustment mode slowly and linearly increases with μ. This high-frequency mode may become unstable at either very strong coupling coefficient or with the large value of $a(x)$. This is consistent with the analytical results of Neelin and Jin (1993) and the argument of Picaut et al. (1997). In the case of the two feedbacks combined (Fig. 2c), the eigenvalue in near the uncoupled regime also

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corresponds to the gravest ocean basin modes. When the coupling coefficient increases, however the damped oceanic adjustment mode transforms into a mixed mode (Jin and Neelin 1993; Neelin and Jin 1993), which becomes the only unstable mode at sufficiently strong coupling. This mode breaks down into two real modes when the coupling coefficient is further increased as it was found in Jin and Neelin (1993).

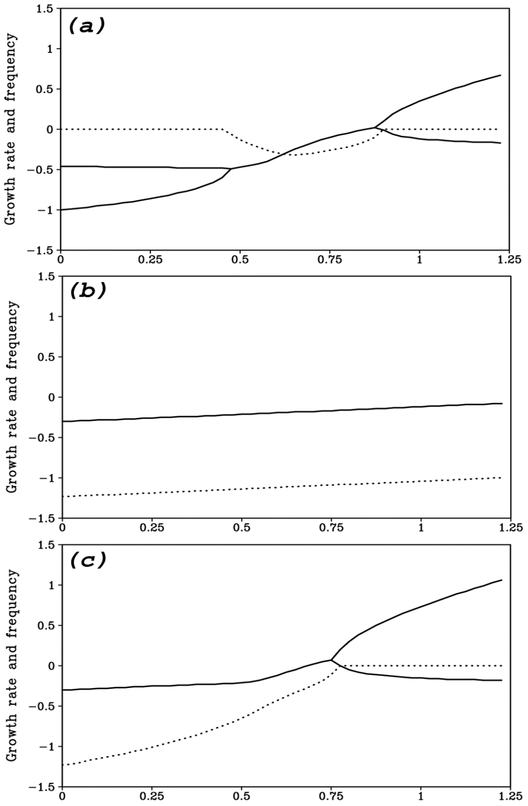

Fig. 1 Dependence of the eigenvalues of the first leading mode on the relative coupling coefficient. The solid curve is for growth, and the dotted curve is for frequency. (a) is for $\gamma(x)=1.0$, $a(x)=0.0$; (b) is for $\gamma(x)=0.0$, $a(x)=1.0$; (c) is for $\gamma(x)=1.0$, $a(x)=1.0$. Axes are frequency and growth rate (year^{-1}). Dividing $\pi/3$ by the frequencies yields period in years.

As shown in Fig. 1, the main difference between the cases with and without the zonal advective feedback occurs in the low coupling regime. The leading unstable mode with both thermocline and zonal advective feedbacks can be traced back to the damped oscillatory ocean adjustment mode by continuously reducing the relative coupling coefficient to zero. However, in the thermocline feedback alone case, the leading mode comes from a merge of the decaying SST mode and the decaying nonoscillatory ocean adjustment mode. The zonal advective feedback tends to destabilize the ocean basin mode (Neelin and Jin 1993). This is because the gravest ocean basin mode has a zonal velocity maximum at the center of equatorial basin as a result of a focus of wave reflection (Cane and Moore 1981). This relatively strong zonal flow anomaly in the central Pacific collocated with the strong SST gradient makes this ocean basin mode effective to produce SST anomaly in the central Pacific. In the strong coupling regime, the characters of the coupled mode are effectively changed (Jin and Neelin 1993). Nevertheless, the coupled mode with zonal advective feedback tends to have a wider range for relatively high frequency. Also one may notice that the neutral point ($\sigma_r=0$) associated with the two feedbacks combined occurs at much lower coupling ($\mu\approx0.67$) than that associated with the case of only thermocline feedback ($\mu\approx0.84$).

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