Dynamics of monsoon-induced biennial variability in ENSO

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Abstract. The mechanism of the quasi-biennial tendency in ENSO-monsoon coupled system is investigated using an intermediate coupled model. The monsoon wind forcing is prescribed as a function of SST anomalies based on the relationship between zonal wind anomalies over the western Pacific to sea level change in the equatorial eastern Pacific. The key mechanism of quasi-biennial tendency in El Niño evolution is found to be in the strong coupling of ENSO to monsoon wind forcing over the western Pacific. Strong boreal summer monsoon wind forcing, which lags the maximum SST anomaly in the equatorial eastern Pacific approximately 6 months, tends to generate Kelvin waves of the opposite sign to anomalies in the eastern Pacific and initiates the turnabout in the eastern Pacific. Boreal winter monsoon forcing, which has zero lag with maximum SST in the equatorial eastern Pacific, tends to damp the ENSO oscillations.

1. Introduction

The presence of a distinctive quasi-biennial (QB) periodicity associated with El Niño is well known. *Lau and Sheu* [1988] found a QB peak in a global rainfall pattern associated with El Niño. *Rasmusson et al.* [1990] and *Ropelewski et al.* [1992] identified spatial patterns of sea surface temperatures and wind associated with the QB variability, similar to that of El Niño. Numerous studies have also reported the presence of strong QB variability in the Asian summer monsoon, involving possibly both regional and Indo-Pacific basin-scale coupled ocean-atmosphere processes [*Yasunari*, 1990; *Meehl*, 1993, 1997; *Shen and Lau* 1995; *Goswami*, 1995]. Recently *Chang and Li* [2000] suggested that QB variability may stem from processes within the Indian ocean and the maritime continent. *Clarke and Shu* [2000] suggested the western Pacific wind anomalies may phase-lock the ENSO to the seasonal cycle.

It is also well-known that the Asian summer monsoon is negative correlated with an El Niño [*Rasmussen and Carpenter*, 1982, *Webster and Yang*, 1992, *Lau and Yang*, 1996 and many others]. *Wainer and Webster* [1996] argued that the interannual variation of the summer monsoon may contribute to irregularities of El Niños. *Chung and Nigam* [1999] showed that, based on results from an intermediate ocean-atmosphere coupled model, that monsoon forcing may increase the frequency of the occurrence of El Niño's. *Yasunari and Seki* [1992] and *Shen and Lau* [1995] suggested that the biennial tendency

is likely to be a fundamental time scale involved in monsoon-ENSO interaction. However, it has never been make clear how the ENSO itself may be affected by the monsoon and why are there strong QB signals in both the ENSO and monsoon. Recently, *Lau and Wu* [2000] showed observational evidence of strong monsoon-ENSO interaction in El Niño's which exhibit strong biennial tendency. They hypothesized that the biennial variability in El Niño is induced by strong monsoon forcing. The objective of this paper is providing a theoretical basis of that hypothesis.

2. The Hypothesis

The basic tenet of the Lau and Wu 's hypothesis is that strong equatorial surface westerlies (easterlies) stemming from an anomalous West Pacific Anticyclone (WPA) in the boreal summer East Asian monsoon system, is instrumental in providing the transition from El Niño to La Nina or vice versa. This situation is illustrated in Fig. 1, which shows the lagged correlation of monthly sea level anomalies in the equatorial eastern Pacific (5°N-5°N, 140°W-120°W) with 1000 mb wind in the equatorial western Pacific (5°S-5°N, 125°E-145°E, solid line) and central Pacific (5°S-5°N, 180°E-160°W, dashed line). The wind data is from the National Center for Environmental Prediction (NCEP) reanalysis [*Kalnay et al.* 1996] and the sea level data is from the NCEP ocean assimilation data [*Ji et al.* 1995]. It is clear that the central Pacific wind has the highest simultaneous correlation with the sea level variability in the eastern Pacific with westerly wind coinciding with the maximum sea level height. In contrast, the western Pacific wind has the highest correlation with the westerly (easterly) wind leading the sea level rise (fall) in the eastern Pacific by approximately six months. There is a significant negative correlation at about 5-month lag, with the western Pacific wind lagging, but at zero lag, the correlation is zero. This suggests that as far as ENSO sea level variability is concern, the central Pacific and western Pacific represent two separate wind systems, exerting their impacts at different phases of the ENSO cycle. As suggested by recent studies, [*Wang et al.*, 1999; *Lau and Wu*, 2000], the zero-lag and 6 month-lag wind forcing in the low latitude western Pacific is related to anomalies in the boreal winter and summer monsoons, respectively.

3. Model Experiments

We use a modified intermediate coupled ocean-atmosphere model of *Zebiak and Cane* [1987] to elucidate the fundamental dynamics of biennial variability in monsoon-ENSO interaction. This model has been used in various theoretical studies of coupled ocean-atmosphere interaction and in experimental seasonal-to-interannual prediction [*Cane et a.,1986*; *Tziperman et al.*, 1998; *Chen et al.*, 1998]. While this model lacks detailed physics of the atmospheric and oceanic processes, it does capture the essential dynamics of El Niño evolution [*Battisti*, 1988; *Zebiak and Cane*, 1987]. One of the major limitations of

the model is the lack of coupled ocean-atmosphere physics and influence from monsoon processes to the west of the dateline. As a result, the model has very weak variability of SST and surface wind in the western Pacific, which are inconsequential to the model ENSO evolution. To mimic the monsoon forcing, an external wind forcing over the western Pacific is prescribed as a function of Nino3 SSTA, with a time lag of either zero or 6 months as follows

$$U_{mons} = -\alpha\, F(T_{EPAC}\,(t - \delta))$$

Where α denotes the magnitude of the coupling between the eastern Pacific SSTA (T_{EPAC}) and the imposed monsoon wind (U_{mons}). A value of $\alpha = 1.0$ corresponds to about 2 m/sec maximum wind speed over the western Pacific, when the Nino3 SST anomaly is 3°K. The time lag δ, between the Nino3 SSTA and the monsoon wind forcing is based on the empirical relationship shown in Fig. 1. The spatial function F, is prescribed as a Gaussian profile in the meridional direction with half-width about 10 degree within the equator, and zonal wind patch between the western edge of the ocean domain (130°E) and the eastern edge of the warm pool 160°E. As we shall show, the present results are insensitive to the details of the spatial distribution, but more to the coupling coefficient, α and the time lag, δ. As discussed previously, this lagged relationship may be attributed to the wind forcing from the two monsoons, i.e. zero lag for the boreal winter and 6 months lag for the boreal summer.

4. Results

We begin with the discussion of the impact of the time delay, and the strength of coupling in the prescribed monsoon forcing on the evolution of ENSO. For the control experiment ($\alpha = 0$), we have chosen typical model parameters so that the model exhibit an ENSO oscillation with pronounced cycle at 3.4 years. As the coupling increases, for $\delta = 0$, the model ENSO oscillations are strongly damped (Fig. 2a). In contrast, for $\delta = 6$ months, the oscillations evolve with increasing frequency locking towards a quasi-QB periodicity (Fig. 2b). It is clear that by the time $\alpha = 2$ (which about doubles the typical present-day value), the model ENSO is locked into a pronounced limit cycle with periodicity of exactly two years. The aforementioned frequency evolution is also apparent in the spectra, as a function of α (Fig. 2 c and d). It is interesting to note that the frequency modulation appears to occur in steps, typical of nonlinear systems. When the coupling coefficient is weak at the range of 0.1 to 0.5, the dominant periodicity is 3 years. A bifurcation occurs at about $\alpha = 0.5$, when multiple periodicities are excited. For $\alpha > 1.0$, increasing frequency locking to the biennial time scale is apparent.

Figure 3 shows the composite time-longitude sections of surface wind and thermocline depth anomalies along the equator for the control ($\alpha = 0$, $\delta = 0$) and for $\alpha = 1.5$, $\delta = 6$. Apparent in the control is an intrinsic oscillation of warm

(El Niño) and cold (La Nina) state with a periodicity of approximately 42 months. Thermocline anomalies propagate eastward and are strongest in the two ends of the ocean domain. Strong coupling of wind and thermocline occur only in the eastern Pacific, with low level convergence (divergence) overlying positive (negative) thermocline anomalies. As stated previous, in the control, the model surface winds are weak in the western Pacific and play no role in the generation of the thermocline anomalies. When an interactive monsoon wind with a time lag of 6 months (with respect to the eastern Pacific thermocline/SST anomaly) is introduced, the model intrinsic oscillation equilibrate to a periodicity of approximately 28 months. In this case, both wind system in the western and the eastern Pacific play important role in the oscillation. Over the eastern Pacific the coupling wind/thermocline mechanism is the same as in the control. However, in the western Pacific, strong phase locking of the anomalies with the seasonal cycle occurs. Here, maximum thermocline anomalies occur in and around boreal winter about 6 months after the maximum monsoon wind forcing in the boreal summer. The eastward propagation of the coupled thermocline and wind anomalies is very pronounced, and takes approximately 12 months to complete. As a result, the entire system oscillates at an approximate cycle of approximately 2 years.

Numerous additional experiments have been carried out with different variations of the monsoon forcing and time lags. One set of experiments is with the monsoon forcing invoked only for December through February (DJF) with zero lag, and for June through August (JJA) with 6 months lags. Yet another set was carried out with imposed stochastic wind forcings added to (1). These variations in wind forcings do not change the nature of the aforementioned results.

5. Summary and Discussions

The present results illustrate a simple, basic mechanism in which monsoon wind forcings in the tropical western Pacific may affect ENSO variation. In the control, the model ENSO cycle can be described in terms of the delay oscillator mechanism [*Suarez and Schopf*, 1988; *Battisti* 1988]. Coupled wind and thermocline/SST anomalies are generated continuously by the action of strong air-sea interaction in the eastern Pacific. The associated cyclonic wind stress curl spawns equatorially trapped westward propagating oceanic Rossby waves, which are reflected as an oceanic Kelvin wave at the western boundary. The upwelling (downwelling) Kelvin wave propagates eastward and generates negative (positive) thermocline anomalies which replaces the existing positive (negative) anomalies and perpetuates the model El Niño cycle. When the monsoon wind forcing is applied with zero lag, an eastward propagating equatorial Kelvin wave is generated producing thermocline perturbation of the opposite sign to an anomaly already existing in the eastern Pacific, effectively annihilating the anomaly in the eastern Pacific.

The ENSO oscillation is therefore strongly damped as illustrated in Fig. 4, which describes the situation that occurs during the boreal winter.

In the case of monsoon wind forcing with 6-month lag, the delayed oscillator mechanisms is strongly modulated by wind forcings in the western Pacific (Fig. 5). Here, maximum thermocline anomaly develops alternatively in the eastern and western Pacific, at about 12 months apart, around boreal winter. In the western Pacific, the thermocline anomaly develops, about 6 months after the maximum monsoon wind forcing, which occurs in the intervening boreal summer season. In the transition, say from cold to warm phase in the eastern Pacific, the monsoon wind forces the thermocline anomaly to change sign, and in doing so sends an upwelling Kelvin wave to the east, initiating a turnabout in the eastern Pacific. This upwelling Kelvin wave enhances and supplants the negative Kelvin wave generated by Rossby wave-reflection at the western boundary by the delayed oscillator mechanism. When both the boreal winter and summer monsoon forcings are imposed, the coupled monsoon-ENSO system equilibrates with increasing coupling toward a biennial see-saw oscillation across the Pacific, with the monsoon acting as a "pace-maker" for the model ENSO oscillation.

It is worth pointing out that the results presented here are highly idealized, so that detailed comparison with actual observations is not warranted. In the model coupled system, the ENSO oscillation period is either 3-4 year or quasi-biennial depending on the strength of the monsoon-ENSO coupling. In reality, both periodicities can occur simultaneously and many other factors can modulate or induce irregularities in ENSO cycles. Nonetheless, the basic mechanisms proposed here is specifically relevant to monsoon forcing and can be further tested in more sophisticated coupled models.

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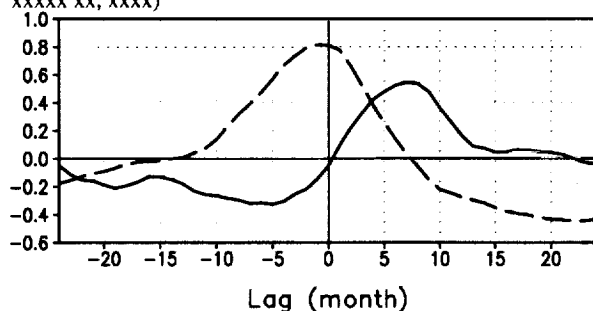
Figure 1. Lag correlation of monthly sea level anomalies in
the equatorial eastern Pacific (5°S-5°N, 140°W-120°W)
with 1000 mb wind in the equatorial western Pacific (5°S-
5°N, 125°E-145°E, solid line) and central Pacific (5°S-5°N,
180°E-160°W, dashed line). Positive lag means wind leads
sea level change.
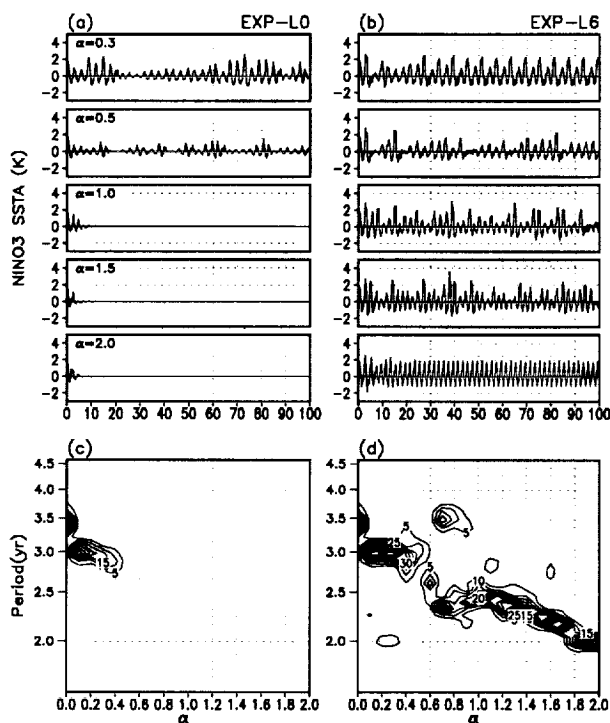
Figure 2. Simulated NINO3 SSTA timeseries (a) and its
power spectra (c) with various range of coupling magnitude
(a) for lag=0. (b) and (d) are same as (a) and (c), except for
lag=6.
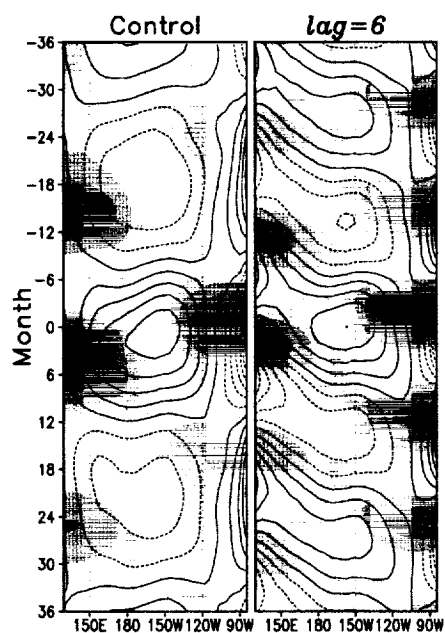
Control lag=6

Figure 3. (a) Composite of simulated thermocline depth (color) and wind stress (contour) anomalies averaged between 2°N and 2°S along the equator for the control run. (b) Same as (a), except for the experiment with lag = 6.
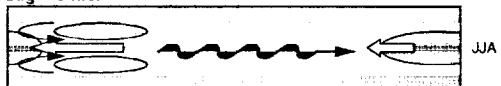
Lag = 0 mo.
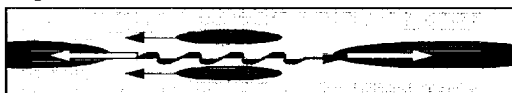
Figure 4. Schematics showing possible interaction of the boreal winter monsoon with ENSO as a damped oscillator.
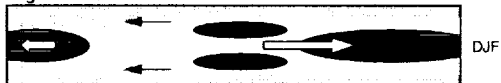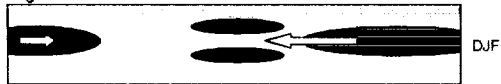
Lag = 0 mo.

Figure 5. Schematics showing a biennial oscillator induced by the interaction of the monsoons (summer and winter) with ENSO.