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 tropospheric biennial oscillation (TBO) associated with El Niño and Asia-Australian monsoon is well known. *Lau and Sheu* [1988] found a biennial 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 quasi-biennial variability, similar to that of El Niño. Numerous studies have also reported the presence of strong TBO 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 TBO 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 negatively correlated with an El Niño [*Rasmusson 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 TBO signals in both the ENSO and monsoon. Recently, *Lau and Wu* [2000] showed observational evidence of strong monsoon-ENSO interaction in El Niño's that exhibit strong biennial tendency. They hypothesized that the biennial variability in El Niño is induced by strong monsoon forcing in the equatorial western Pacific. The objective of this paper is providing a theoretical basis of that hypothesis.

2. Western Pacific wind anomalies

Recently Weisberg and Wang [1997] and Wang et al [1999] showed that the far western Pacific and the central Pacific constitute two separate surface wind systems in governing ENSO variability. This situation is illustrated in Fig. 1, which shows the lagged 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). 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] from January 1980 to August 1998. 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 also a significant negative correlation at about 5-6 month lag. The correlation suggests a biennial tendency in the surface wind in the western Pacific with respect to the thermocline variability in the eastern Pacific. However, it does not necessarily mean that the surface wind is directly forced from the eastern Pacific. The time delay of western Pacific wind anomalies may stem from air-sea interaction

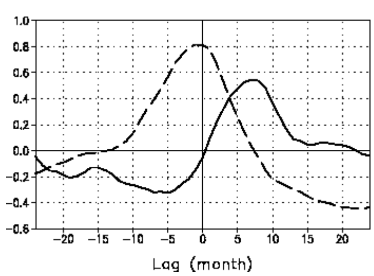

Figure 1. Lag correlation of monthly sea level anomalies in the equatorial eastern Pacific (5°S-5°N, 140°W-120°W) with 1000 mb wind in the equatorial western Pacific (5°S-5°N, 125°E-145°E, solid line) and central Pacific (5°S-5°N, 180°E-160°W, dashed line). Positive lags mean that changes in wind lead those in sea level.

associated with the development of off-equatorial SST anomaly in the western Pacific (Wang et al. 1999). Alternatively, the wind anomalies may be related to the excitation of an anomalous West Pacific anticyclone (Lau and Wu 2000, Wang et al 1999). Another possibility is the propagation of wind anomalies from the Indian Ocean (Barnett 1984, Shen and Lau 1995). All these mechanisms are likely be linked to anomalies in the boreal summer and winter Asian monsoons.

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 al.,* 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 the 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 Because the seasonal cycle is specified in the model, the seasonal variation of monsoon implicitly plays a role in the model. Both the interannual and intraseasonal variability of the monsoon may affect ENSO. In this study, we only focus on the interannual component that is associated with El Nino. Subseasonal component is neglected in this study because the model is not sensitive to these shorter time scale forcings (Cane 1995).

Because of limited domain and model physics, monsoon effects cannot be fully included. Therefore the monsoon wind forcing over the equatorial western Pacific is only considered. Based on the previous studies and the

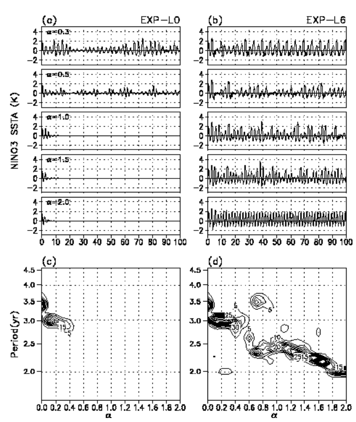

Figure 2. Simulated NINO3 SSTA time series (a) and its power spectra (c) with various range of coupling magnitude (α) for lag=0. (b) and (d) are same as (a) and (c), except for lag=6. Units of (c) and (d) are (K^2/f).

observational evidence shown in Fig. 1, the monsoon wind forcing is parameterized as a linear relation between NINO3 SSTA and monsoon wind forcing as follows.

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

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 α=1.0 corresponds to about 2 m/sec maximum wind speed over the western Pacific, when the Nino3 SST anomaly is 3K. The time lag δ, between the Nino3 SSTA and the monsoon wind forcing is based on the 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. In the following discussion, we will describe the temporal variations of El Nino, using SST anomalies averaged over the eastern Pacific (NINO3 SSTA). For propagating features, we use thermocline depth anomalies which is the only model variable corresponding to sea level.

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 (α=0), we have chosen typical model parameters so that the model exhibits an ENSO oscillation with pronounced cycle at 3.4 years. As the coupling increases, for δ=0, the model ENSO oscillations are strongly damped (Fig. 2a). In contrast, for δ= 6 months, the oscillations evolve with increasing frequency locking towards a biennial periodicity (Fig. 2b). It is clear that by the time α=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 α= 0.5, when multiple periodicities are excited. For α>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 (α=0, δ=0) and for α=1.5, δ=6. Apparent in the control is an intrinsic oscillation of warm (El

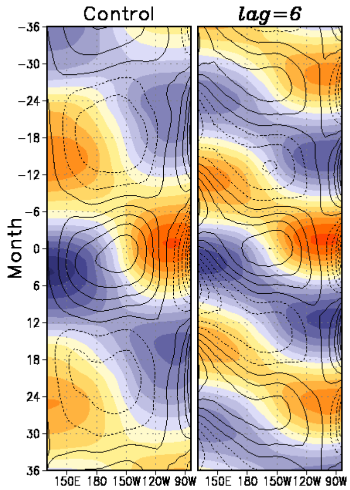

Figure 3. (a) Composite of simulated thermocline depth (color) and wind stress (contour) anomalies averaged between 2°N and 2°S along the equator for the control run. (b) Same as (a), except for the experiment with lag = 6.

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 equilibrates 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

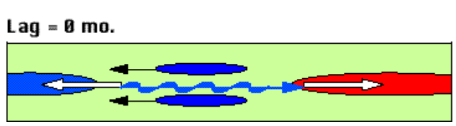

Figure 4. Schematics showing possible interaction of the boreal winter monsoon with ENSO as a damped oscillator. Shaded patches represent the sea level anomalies. Open arrows indicate zonal wind anomalies. Thin and wavy arrows represent the Rossby and Kelvin wave propagation, respectively.

complete. As a result, the entire system oscillates at a 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 forcing added to (1). These variations in wind forcing 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 forcing 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 mechanism is strongly modulated by wind forcings in the western Pacific. The sequence of events is shown schematically in 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

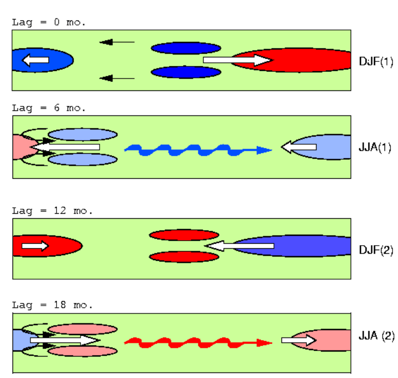

Figure 5. Schematics showing a biennial oscillator induced by the interaction of the monsoons (summer and winter) with ENSO. Arrows and shaded patches are same as in Fig. 4.

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 JJA(1) in the eastern Pacific, the monsoon easterly wind forces the thermocline anomaly to increase in the far western Pacific, 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, eventually leading to the establishment of the cold phase in DJF(2). This is followed by the development of westerly wind anomalies in the western Pacific 6 months later in JJA(2). The biennial cycle then repeats. Hence the imposed monsoon forcing cause the coupled monsoon-ENSO system to equilibrate 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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