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A NEAR-ANNUAL COUPLED OCEAN-ATMOSPHERE MODE IN THE EQUATORIAL PACIFIC OCEAN

Soon-Il An[1], Fei-Fei Jin[1], Jong-Seong Kug[2], In-Sik Kang[2]
[1]School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, Hawaii
[2]School of Earth and Environmental Sciences, Seoul National University, Seoul, Korea

1. INTRODUCTION

In the past two decades major progress has been made in understanding and modeling the coupled ocean-atmosphere interactions in the tropical Pacific and the salient features of the ENSO phenomenon (Wallace et al. 1998, McPhaden et al. 1998, Neelin et al. 1998). The physical mechanisms responsible for the generation of the ENSO phenomenon are now largely understood. Tropical Pacific climate variability is often characterized by index time series such as the "Niño 3" sea surface temperature anomalies (SSTA) and the Southern-Oscillation index. Their observed spectra exhibit much more structure than just a single spectral peak at interannual timescales associated with ENSO. In addition to the 3-5 year main periodicity of ENSO, there is significant variance on various other time scales, and in particular at near annual periods. The physical origin of this near-annual residual variability, which has been viewed by many scientists as an expression of "noise", has not been disentangled yet. We will show that these fast fluctuations are associated with an overlooked coupled mode of the tropical Pacific atmosphere-ocean system.

Evidence for the co-existence of different coupled modes in the tropical climate system was in fact found in a number of coupled models. For instance, in the Zebiak and Cane (1987, ZC hereafter) a fast mode, called the "mobile mode" (Zebiak, 1984, Mantua and Battisti, 1995, Perigaud and Dewitte, 1996), can be identified that is characterized by a 9-12 month period and that can co-exist with the simulated interannual ENSO mode. Similar co-existences between fast and slow modes have been found also in more complex models (Neelin 1990, Philander et al. 1992). So far, however, the relevance of these simulated fast modes has not been recognized. Using the NCEP ocean assimilation data set (Ji et al. 1994), we will present observational evidence for a fast mode with a period of about 12 to 18 months. It bears some similarity with the so-called "mobile mode" simulated by the ZC model (Mantua and Battisti, 1995).

2. OBSERVATIONAL EVIDENCE FOR A COUPLED FAST MODE

Fig.1 shows the eastern equatorial Pacific SSTA (from Reynolds and Smith, 1994) averaged over the region 170W-120W and 2S-2N. As can be seen from the raw time series and its wavelet transform there is significant variability on a 12 to 18 month period in addition to the interannual ENSO cycle. Near-annual variability is most pronounced during the 1970s and 1990s. As can be seen for the earlier 90's, superimposed on a warm background state, some of these relatively fast temperature fluctuations turn into mini-El Niño events. Fluctuations with a similar time scale occurred between all major El Niño events and in particular in the aftermath of the 1997-1998 event. Using the NCEP ocean assimilation data set (Ji et al. 1994), we scrutinize the 24-month high-pass filtered monthly data from 1991-2001. As can be seen from Figure 2 the SST, zonal wind, zonal current and sea level anomalies are all closely related to each other. Figure 2 documents the existence of some near-annual SST and wind-stress fluctuations after 1998 that exhibited some westward propagation from the central to western Pacific. This propagating feature is less clear in the ocean current and sea level anomalies. These near annual anomalies are phase locked to the climatological annual cycle that has been subtracted prior to the analysis. Their propagation characteristics resemble those of the climatological annual cycle in the equatorial eastern Pacific. Hence they represent an enhancement of the mean annual cycle in the eastern equatorial Pacific. Unlike the mean annual cycle, however, these near annual anomalies extended much farther to the west. In contrast to the late 1990s, the anomalies in the early 90s did not exhibit any westward propagating features. Furthermore, their period of 16-18 months was somewhat longer than in the late 90s. Despite of these differences, the fast fluctuations shown in Fig.2 share many common features, such as the presence of strong zonal current anomalies.

A more detailed perspective on the physical mechanism that generates the fast mode of variability is obtained by studying the near-annual fluctuations after the 1997-1998 El Niño event. The anomalous SST, zonal wind stress, zonal current, and sea level height are now defined by removing the climatological annual cycle and a local linear trend based on the period from the end of 1998 to the end of 2001. The spatial patterns associated with the fairly regular post-1998 near annual oscillations are shown in Fig.3 using the composite maps of the extreme- and transition-phases. During the mature warm phase (Figure 3, left panels), the SST pattern is located in the central and eastern equatorial Pacific. In response to these SST anomalies, westerly wind stress anomalies emerge in the western equatorial Pacific and easterly wind stress anomalies in the eastern Pacific. These zonal wind stress anomalies drive anomalous zonal currents, thereby amplifying an eastern and central Pacific warming.

Furthermore, positive sea-level anomalies can be observed indicating relatively warm subsurface temperature anomalies. In the far eastern equatorial Pacific, anomalous vertical advection (not shown) also plays a crucial role in generating SST anomalies. During the transition phase of the fast mode (Figure 3, right panels), anomalous zonal currents have reversed throughout the whole equatorial Pacific as a result of the easterly winds three months prior to the transitions phase. During the phase reversal stage equatorial sea-level anomalies are close to zero. The anomalous zonal advection of cold eastern equatorial Pacific upwelling waters enhances the negative SST anomaly and leads to a westward propagation of the cold anomaly. It is the interplay between local SST/advection feedbacks, the non-local atmospheric response to SST anomalies and the westward propagation of SST anomalies due to changing currents that gives rise to this coupled mode of variability.

As already pointed out by Mantua and Battisti (1995), the fast mode of variability had a significantly reduced amplitude during the 1980s. Apparently this fast mode has undergone some decadal changes in its propagation characteristics and periodicity, which can be partly explained by an interaction of the fast mode with the slow ENSO mode. For instance, the extended cold phase after the 1997/98 El Niño event provided a modified background for the fast mode of variability. The lingering La Niña state in the post 1998 era was characterized by strong zonal SST gradients that are expected to favor the westward propagation feature of the fast mode, whereas relatively warm background in earlier 90s might have been responsible for a suppression of the westward propagation feature. During the early 1990s warmer background conditions might have enhanced the thermocline feedback as found in An and Jin (2001) for the case of the ENSO mode. When the coupled fast mode has its intrinsic frequency close to the forced annual frequency, phase- and frequency locking are likely to occur as seen in the aftermath of the 1997/98 El Niño event. In the early 1990s, however, the frequency of the coupled mode was lower than the annual frequency thereby reducing the potential for nonlinear phase-locking to the annual cycle.

3. MODELING EVIDENCE FOR FAST COUPLED MODE

Here we show an example from a long simulation using the standard ZC model illustrating that the fast coupled mode can be easily locked to an annual cycle background forcing. Figure 4 reveals that the fast fluctuations superimposed on the slow ENSO mode occur preferentially during the La Niña phases. These fast fluctuations are related to the 9-10 month “mobile mode” in the model. In the later part of the model simulation when the slow ENSO cycle disappears, there is a pronounced fast mode with its frequency almost locked to the annual frequency. The simulated fast mode has a stronger westward-propagating tendency and a shorter periodicity than seen in Fig.2. The causes for this pronounced westward propagation and the relatively short periodicity are still under further investigation. Yet, the general characteristics of the simulated anomalies in SST, zonal winds, zonal currents, and thermocline depth are similar to the observations as can be seen from a comparison of Fig.2 and Fig.4 focusing on the post 1998-period. These model results indicate that frequencies of the fast mode may change depending on the strength of nonlinearity that is responsible for frequency locking.

4. DISCUSSION AND CONCLUSION

We conclude that the fast mode seen in the observations may be viewed as an independent coupled mode of variability that is modulated by ENSO and annual cycle forcing. Westward SST propagation characteristics seem to be favored when an enhanced zonal SST gradient exists in the equatorial Pacific. The fast coupled mode identified in the ocean assimilation data set shares many similarity with the so-called “mobile mode” in the ZC model. The main positive feedback and phase transition mechanism for this fast mode are provided by the zonal advection feedback which can generate coupled air-sea modes as first suggested by Gill (1985).

The important role of zonal advection anomalies for the fast fluctuations leads us to another trace: The Pacific ocean-basin (POB) mode is also associated with strong stationary current oscillations in the central equatorial Pacific (Cane and Moore 1981). In combination with the zonal advective feedback discussed above, the POB can be easily destabilized thereby giving birth to a coupled POB mode with little zonal propagation in the ocean currents and sea-level anomalies. In particular, the analytical solution of Neelin and Jin (1993) bears similarities with the dynamics shown in Fig.2, such as a near-annual periodicity and relatively large zonal current anomalies in the central equatorial Pacific. A heat budget analysis using the ocean assimilation data set (not shown) revealed that anomalous zonal advection dominates the SST tendency in the central Pacific, whereas anomalous Ekman upwelling governs the heating in the far eastern Pacific. We thus suggest that the observed fast mode is to a large extent a coupled POB mode that also exhibits some features of the westward- propagating coupled SST mode (Neelin 1991, Jin and Neelin 1993).

The co-existence of this coupled fast mode and the coupled slow ENSO mode enriches the coupled variability in the tropics and poses a challenge for ENSO predictions. When the background in the equatorial central to eastern Pacific is warm, such as in early 1990's, this fast mode variability may surface as near-annual mini-El Niño events, whereas during cold background the fast mode is expected to lead to near-annual La Niña events such as in the past few years. Further studies are needed for a better understanding of this fast mode variability and its interaction with the slow ENSO mode. We conjecture that this research will help to improve predictions of major and minor El Niño and La Niña events and reduce the false-alarm rate of many models.

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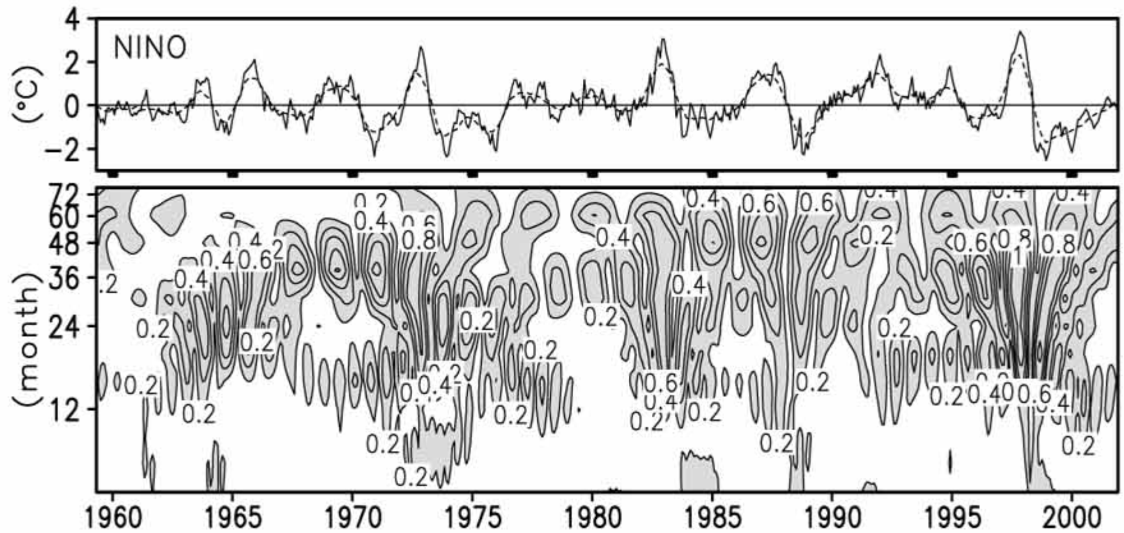

Figure 1. a) Time series of SST anomalies averaged over 170o W-120oW and 2oS-2oN. Solid and dashed line indicates unfiltered and 22-month low pass filtered data, respectively. b) Wavelet spectrum of the time series.

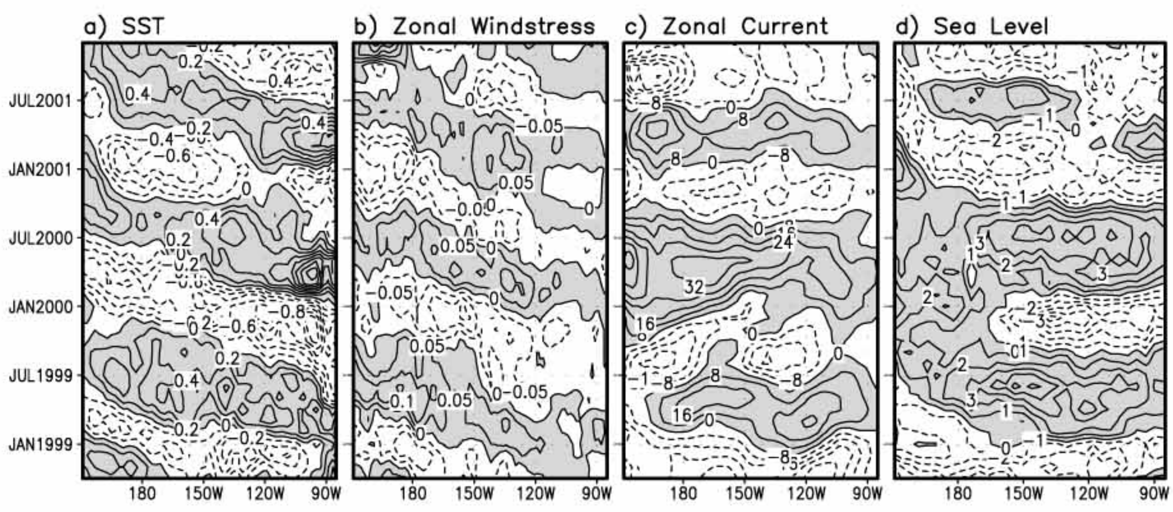

Figure 2. Hovmøller diagrams of the anomalies in SST (unit: oC), zonal wind stress (unit: dyn/cm2), zonal currents (unit: cm/s) and sea level (units: cm) for the period of 1991–2001.

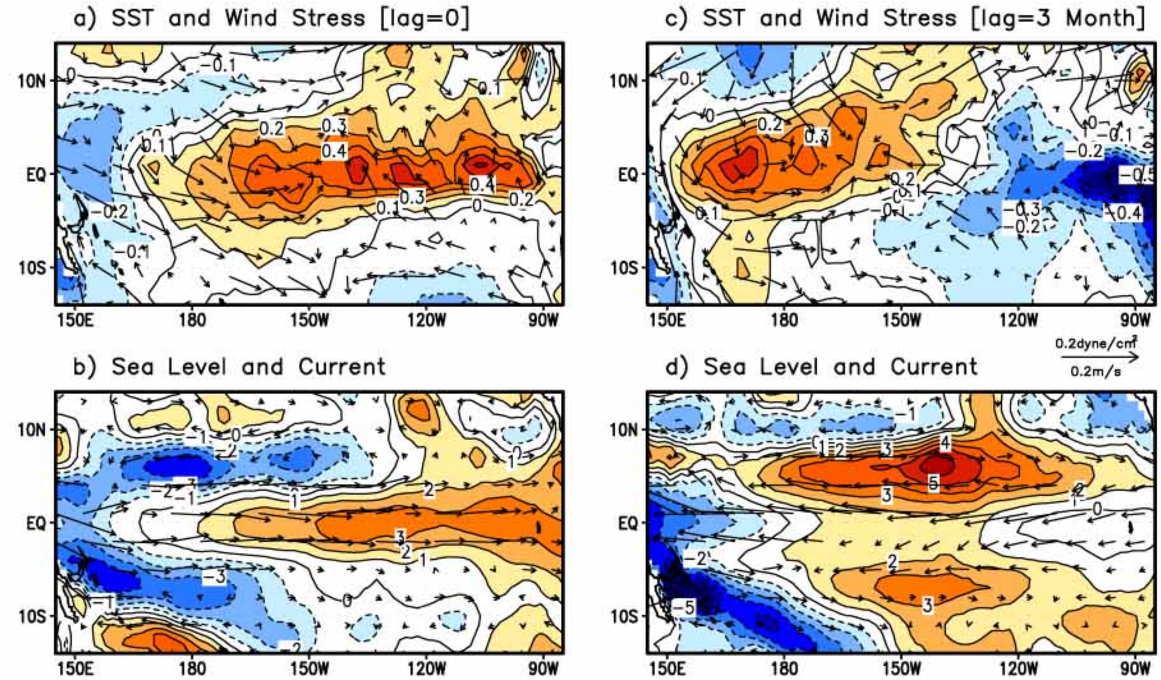

Figure 3. Composite of SST and wind stress anomalies, sea-level and ocean surface current anomalies at the extreme phase and transition phase of the coupled fast mode which are about 3 months apart.

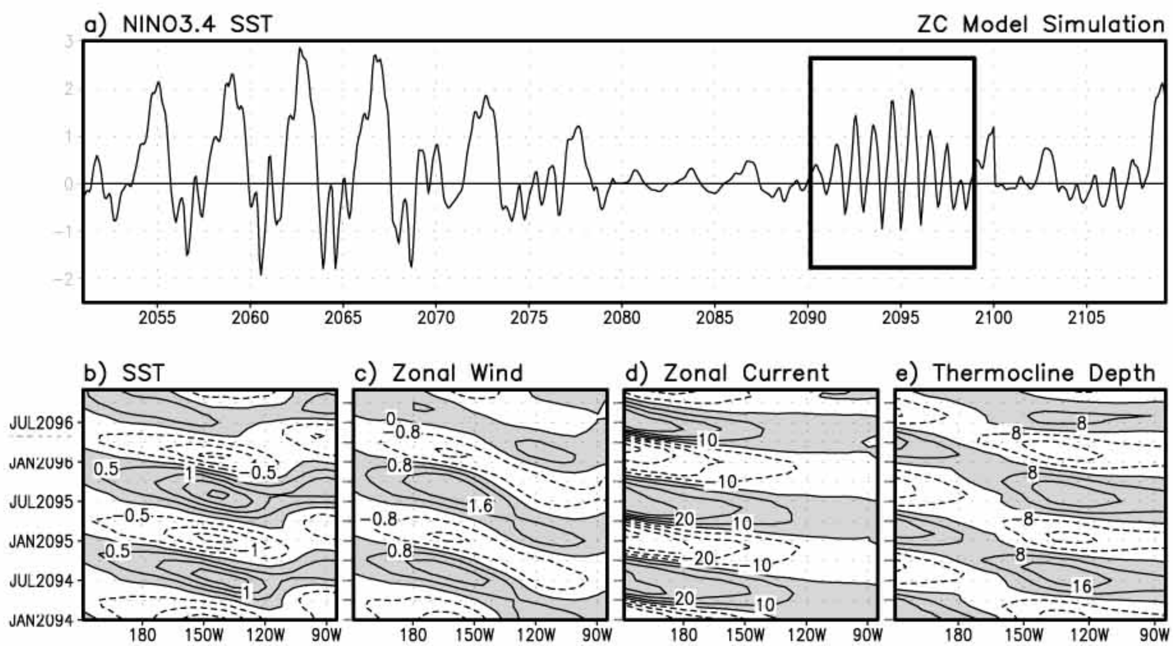

Figure 4. a) A segment of Niño 3 time series of a long integration of ZC model and b) Hovmøller diagram of the anomalies in SST (unit: oC), zonal wind stress (unit: dyn/cm2), zonal currents (unit: cm/s) and thermocline depth (units: m) from the same simulation.