A near-annual coupled ocean-atmosphere mode in the equatorial Pacific ocean

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Received 26 July 2002; accepted 25 November 2002; published 28 January 2003.

[1] A near-annual coupled ocean-atmosphere mode in the equatorial Pacific is studied using the NCEP ocean assimilation data set. This fast mode of tropical Pacific climate variability is superimposed on the slow 3–5 year El Niño-Southern Oscillation (ENSO) phenomenon. Anomalous zonal advection plays a crucial role in generating this fast mode. It is suggested that this fast mode can be understood in terms of a coupled Pacific basin mode. It is responsible for the occurrence of some minor El Niño and La Niña events and has implications for the prediction of ENSO events. *INDEX TERMS:* 4522 Oceanography: Physical: El Niño; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4215 Oceanography: General: Climate and interannual variability (3309); 4504 Oceanography: Physical: Air/sea interactions (0312); *KEYWORDS:* Coupled Fast Mode, El Nino-Southern Oscillation. **Citation:** Jin, F.-F., J.-S. Kug, S.-I. An, and I.-S. Kang, A near-annual coupled ocean-atmosphere mode in the equatorial Pacific ocean, *Geophys. Res. Lett.*, *30*(2), 1080, doi:10.1029/2002GL015983, 2003.

1. Introduction

[2] 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.

[3] 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 *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.*, 1995], we will present observational evidence for a fast mode with a period of about 12 to 18 months. It bears some similarity to the so-called "mobile mode" simulated by the ZC model [*Mantua and Battisti*, 1995].

2. Observational Evidence for a Coupled Fast Mode

[4] Figure 1 shows the eastern equatorial Pacific SSTA [*Reynolds and Smith*, 1994] averaged over the region 170°W–120°W and 2°S–2°N. 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 1990'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.*, 1995], we scrutinize the 22-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 1990s did not exhibit any westward propagating features. Furthermore, their period of 16–18 months was somewhat longer than in the late 1990s. Despite these differences, the fast fluctuations shown in Figure 2 share many common features, such as the presence of strong zonal current anomalies.

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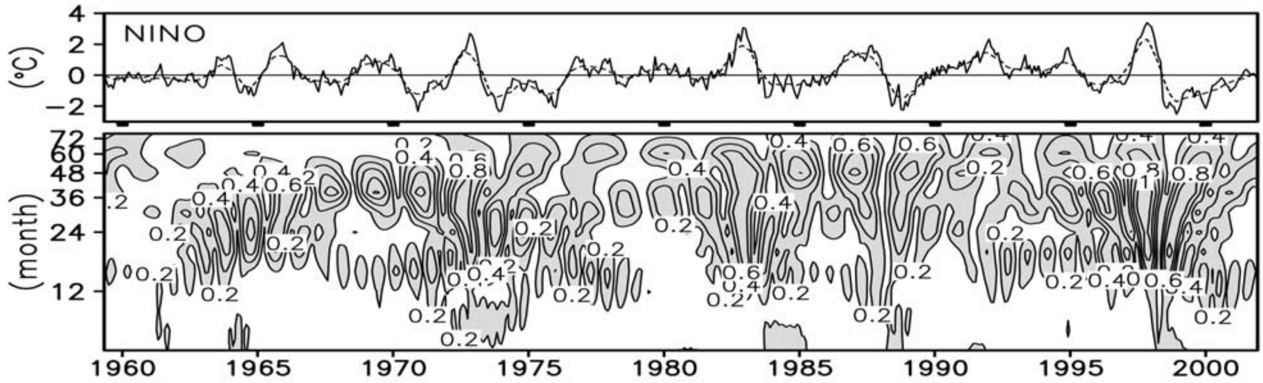

Figure 1. (a) Time series of SST anomalies averaged over 170°W–120°W and 2°S–2°N. Solid and dashed line indicates unfiltered and 22-month low-pass filtered data, respectively. (b) The real part of the Morlet wavelet spectrum of the time, showing the amplitude as a function of oscillation period and time.

[5] 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 Figure 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 through warm advection. 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 entire equatorial Pacific. These current anomalies are largely associated with the reflected

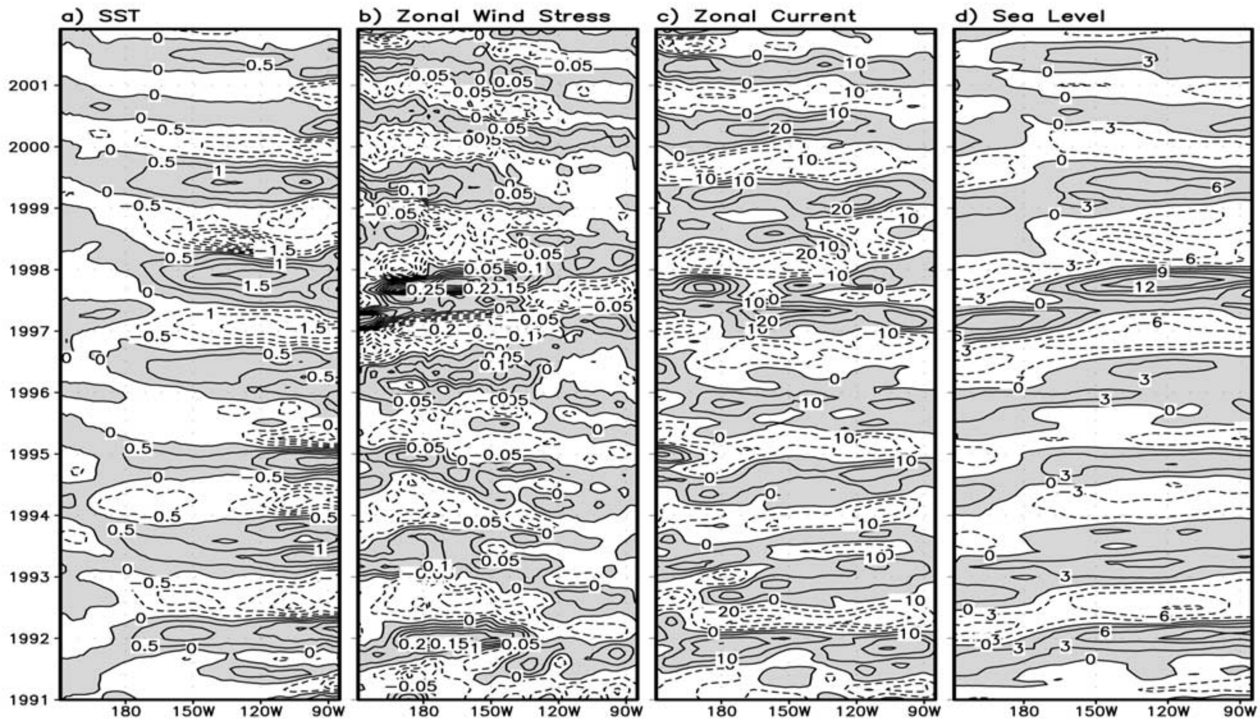

Figure 2. Hovmøller diagrams of the anomalies in SST (unit: °C), zonal wind stress (unit: dyn/cm^2), zonal currents (unit: cm/s) and sea level (units: cm) for the period of 1991–2001.

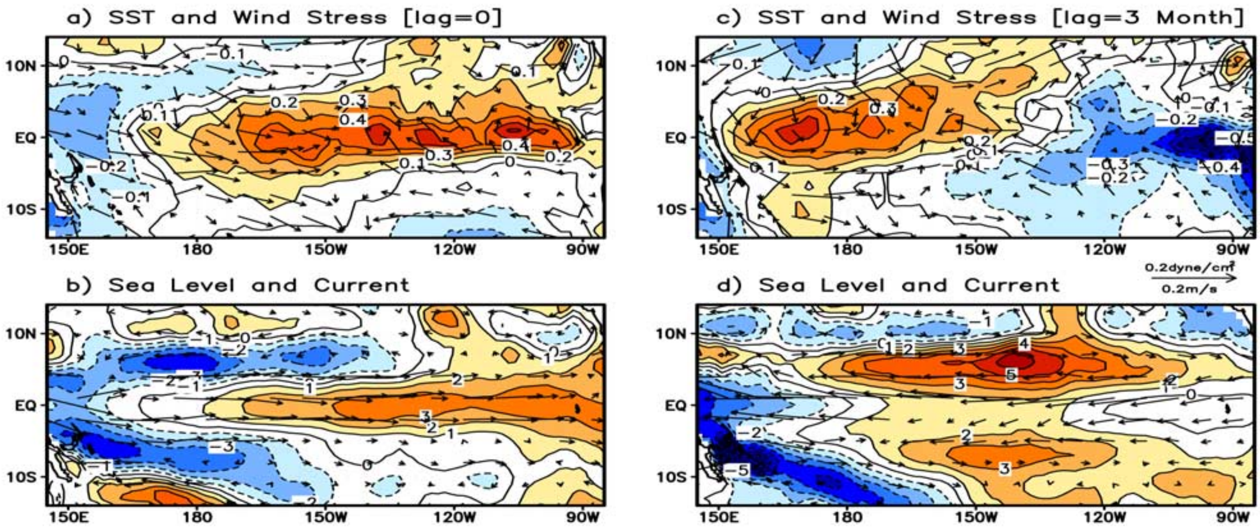

Figure 3. Composite of SST and wind stress anomalies, sea-level and ocean surface current anomalies at the extreme phase and transition phase of the coupled fast mode which are about 3 months apart.

Rossby waves from the eastern boundary and the Rossby waves forced by the easterly wind anomalies in the central and eastern Pacific. The anomalous zonal advection of cold eastern equatorial Pacific waters enhances the negative SST anomaly and leads to spreading of the cold anomaly westward. Therefore, the anomalous zonal advection through the atmosphere-ocean coupling serves as not only a growth but also a phase transition mechanisms of this coupled mode.

[6] 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. 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

[7] 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 of 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. There is a slow ENSO mode with a period of about 4-years nearly frequency locked to the annual cycle. When the slow mode is strong, the fast mode of period about 9–10 months is not locked to annual frequency. This is because the nonlinear interaction of the annual cycle and the slow ENSO mode can create a combination frequency that is the same as that of the fast mode. 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 Figure 2. The causes for this pronounced westward propagation and the relatively short periodicity are still under 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 Figures 2 and 4, particularly after 1998. 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

[8] 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 the 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 similarities with the so-called "mobile mode" in the ZC model. The main positive feedback and phase transition mechanisms for this fast mode are provided by the zonal advection feedback, which can generate coupled air-sea modes as first suggested by *Gill* [1985].

[9] The important role of zonal advection anomalies for the fast fluctuations is related to the fact that Pacific ocean-basin (POB) mode is associated with strong stationary

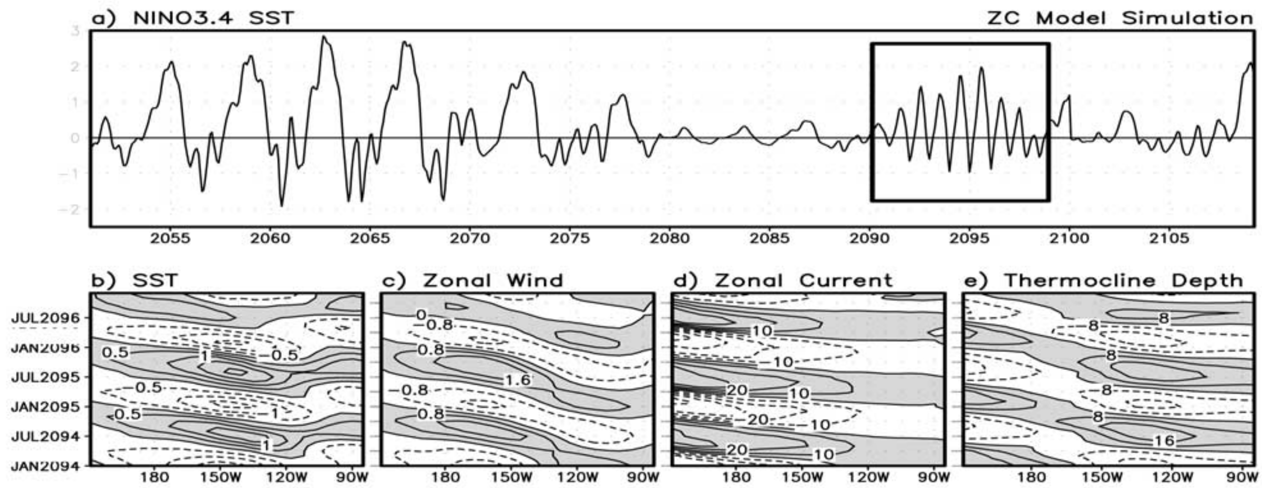

Figure 4. (a) A segment of Niño 3 time series of a long integration of ZC model and (b) Hovmøller diagram of the anomalies in SST (unit: °C), zonal wind stress (unit: dyn/cm^2), zonal currents (unit: cm/s) and thermocline depth (units: m) from the same simulation.

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 to the dynamics shown in Figure 2, such as a near-annual periodicity and relatively large zonal current anomalies in the central equatorial Pacific. The results from Figure 3 also imply a large contribution to the zonal current anomaly from the equatorial waves. Moreover, 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].

[10] 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 the 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.

[11] **Acknowledgments.** This work was partly supported by NSF grants ATM-9615952 and ATM-0226141 and NOAA grants GC99234 and GC01246. Dr. An has been supported by Frontier Research System for Global Change through its sponsorship of the International Pacific Research Center, Prof. Kang and Mr. Kug are supported by the SRC program of Korea Science and Engineering Foundation and the Brain Korea 21 project. The authors thank Drs. Axel Timmermann, Nathan Mantua, and Jingxia Zhao for valuable comments and Diane Henderson for editing the manuscripts. SOEST # 6046 and IPRC # 178.

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