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Equatorial waves and the 1997–98 El Niño

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Abstract. New measurements and model results highlight the role of equatorial oceanic wave processes in affecting the evolution of the 1997–98 El Niño in ways not fully anticipated by delayed oscillator theory, a leading paradigm for the El Niño/Southern Oscillation (ENSO) cycle. The onset of the El Niño was linked to eastward propagating equatorial Kelvin waves forced by intraseasonal atmospheric oscillations originating over the Indian Ocean. The demise of the El Niño was related to a complex interplay of wind-forced and western boundary-forced waves that preconditioned the ocean to sudden sea surface temperature cooling initially centered between 125°W and 170°W along the equator. These large-scale ocean wave processes, and the ocean-atmosphere interactions that they mediate, have significant implications for understanding variability associated with El Niño-related climate swings.

1. Introduction

Virtually all theories of the ENSO cycle ascribe a central role to equatorial oceanic wave processes which affect sea surface temperature (SST) and subsequent ocean-atmosphere interactions through redistribution of upper ocean heat content. For example, according to delayed oscillator theory, a leading paradigm for ENSO [*Schopf and Suarez*, 1988; *Battisti*, 1988], trade wind-forced downwelling equatorial Rossby waves build up heat content in the western Pacific prior to the onset of El Niño events. Reflection of these waves off the western boundary initiates El Niño by generating eastward propagating equatorial Kelvin waves that depress the thermocline in the eastern Pacific, favoring the development of warm SST anomalies there. A similar set of processes is presumed to work for the termination of El Niño. Upwelling Rossby waves generated by the initial collapse of the trade winds are hypothesized to reflect at the western boundary into upwelling Kelvin waves which propagate eastward to elevate the thermocline in the eastern Pacific, leading to unusually cool SSTs. The cyclic nature of ENSO in this scenario results from a combination of unstable ocean-atmosphere interactions in the equatorial cold tongue region, and delayed negative feedbacks on anomaly growth through wave reflections at the western boundary. However, there has been considerable debate as to whether delayed oscillator theory as originally conceived can account for the full range of variability associated with the ENSO cycle [*Li and Clarke*, 1994; *Mantua and Battisti*, 1994; *Picaut et al.*, 1997; *Weisberg and Wang*, 1997].

In this study we examine the excitation and propagation of equatorial waves during the 1997–98 El Niño using a dynamical wind-forced ocean model. Satellite and in situ data sets help guide the interpretation of the model which, because of its simplicity, allows us to clearly identify the sources of energy for these waves which played a crucial role in the evolution of the El Niño. Our analysis complements that of *Boulanger and Menkes* [1999], who used a linear inverse model to study equatorial wave processes during the period 1992–98.

2. Observational Background

The 1997–98 El Niño was by some measures the strongest on record [*McPhaden*, 1999]. It began in early 1997 with a weakening and reversal of the trade winds and the rapid growth of (SST) anomalies in the equatorial Pacific (Figure 1). The western Pacific warm pool (surface waters with temperatures greater than about 29°C) migrated eastward with the collapse of the trade winds; and the equatorial cold tongue, the strip of cool water indicative of equatorial upwelling that normally occupies the eastern and central Pacific, failed to develop in boreal summer and fall 1997. By December 1997, maximum SST anomalies exceeded 5°C in the cold tongue region. After a slow decline in the intensity of these thermal anomalies in early 1998, the event abruptly ended with an unprecedented 8°C SST drop in one 30-day period during May–June 1998.

For at least a year prior to the onset of the El Niño there was a buildup of heat content in the western equatorial Pacific (Figure 2) due to stronger than normal trade winds associated with the weak 1995–96 La Niña (Figure 1). This buildup set the stage for an El Niño to occur. However, timing of the El Niño onset coincided with a series of westerly wind events along the equator. These westerlies were the surface manifestation of the Madden-Julian Oscillation (MJO), an eastward propagating, 30- to 60-day wave-like disturbance in the atmosphere originating over the Indian Ocean. This episodic wind forcing excited a sequence of eastward propagating, downwelling equatorial Kelvin waves (Figure 1) which left the eastern Pacific thermocline over 90 m deeper than normal in late 1997. The greatly depressed thermocline led to record high SST anomalies at that time.

In early 1998, westerly wind anomalies along the equator abated and migrated eastward with the pool of 29°C water, while easterly wind anomalies appeared in the far western Pacific. Thermocline shoaling, originally confined to the western Pacific, progressed slowly into the central

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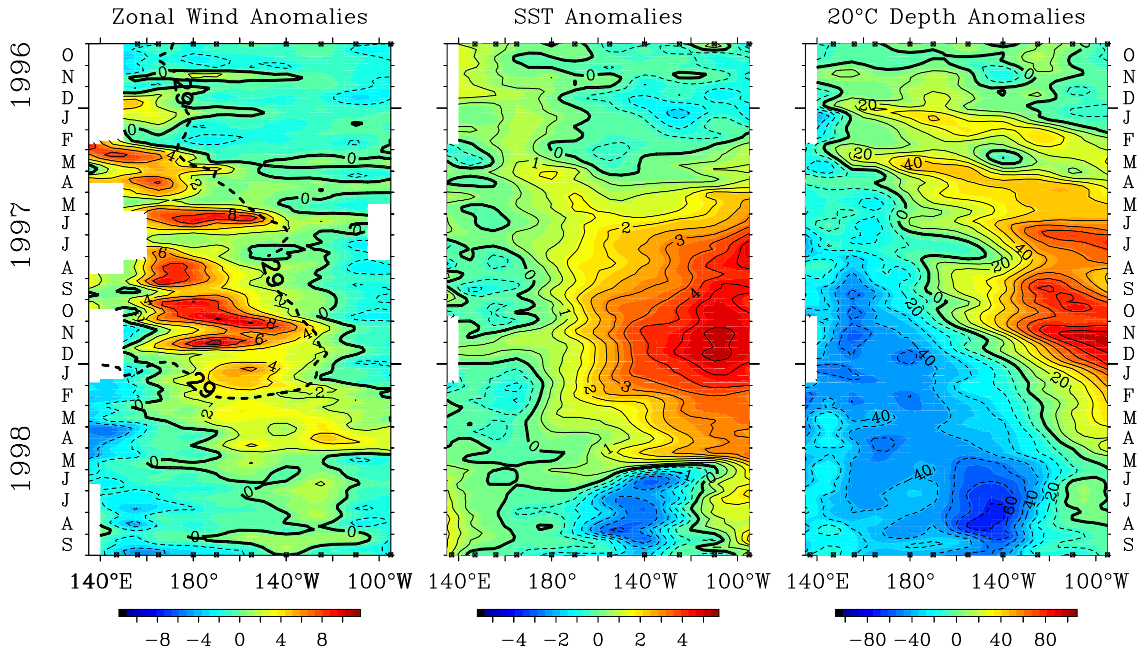

Figure 1. Anomalies in surface zonal wind (in m s^{-1}, left), sea surface temperature (in °C, middle), and 20°C isotherm depth (in m, right) from October 1996 to September 1998. Analyses are based on 5-day averages of moored time series data between 2°N–2°S from the Tropical Atmosphere Ocean (TAO) Array*McPhaden* [1999]. Heavy dashed line in the left panel is for the 29°C isotherm through early 1998.

and eastern Pacific in 1998. SSTs remained unusually high in the eastern Pacific at this time though because the local trade winds were weak there (Figure 1). It was not until the trade winds abruptly returned to near normal strength in the eastern Pacific in mid-May 1998 that the cold subsurface waters could be efficiently upwelled and mixed into the surface layer.

3. Model Formulation and Results

We use the model of *Yu and McPhaden* [1999], which is based on the method of characteristics, to solve for the first four vertical baroclinic mode equatorial Kelvin waves and six greatest meridional mode equatorial Rossby waves. The model is forced for the period January 1985 to Septem-

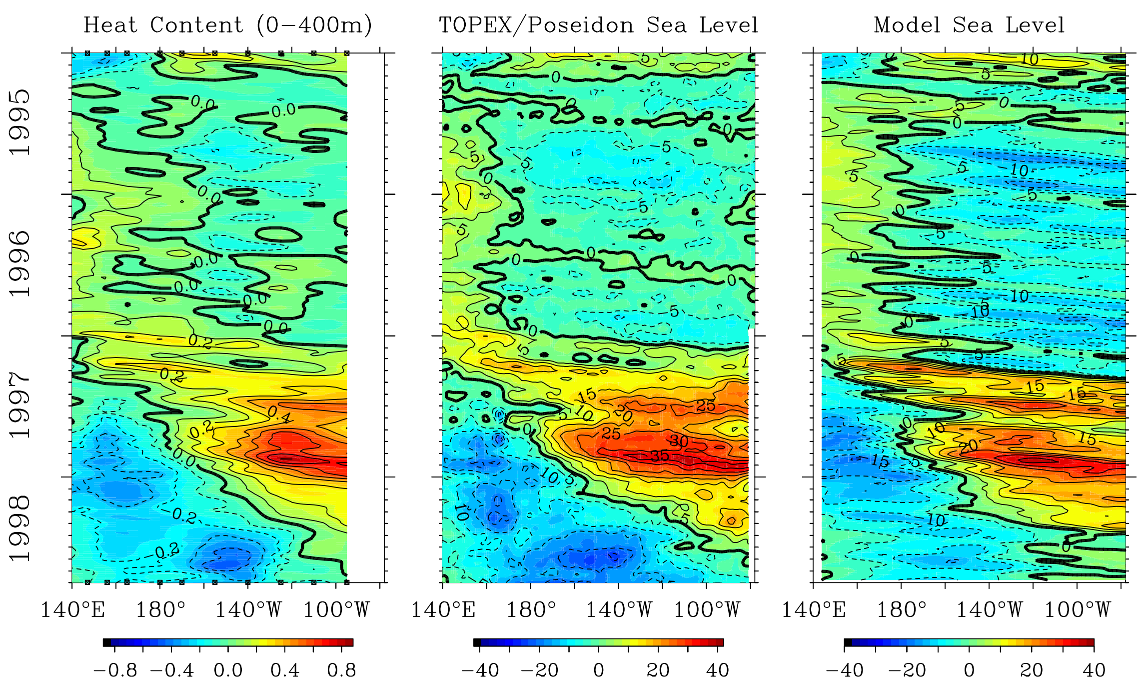

Figure 2. Heat content anomalies averaged between 2°N and 2°S along the equator from TAO data (in 10^{10} J m^{-3}, left), sea level anomalies along the equator from the TOPEX/Poseidon altimeter (in cm, middle), and modeled sea level anomalies along the equator (in cm, right). Temporal resolution is 5-days for TAO data and the model, 10-days for the altimeter data. A mean seasonal cycle has been removed from each time series.

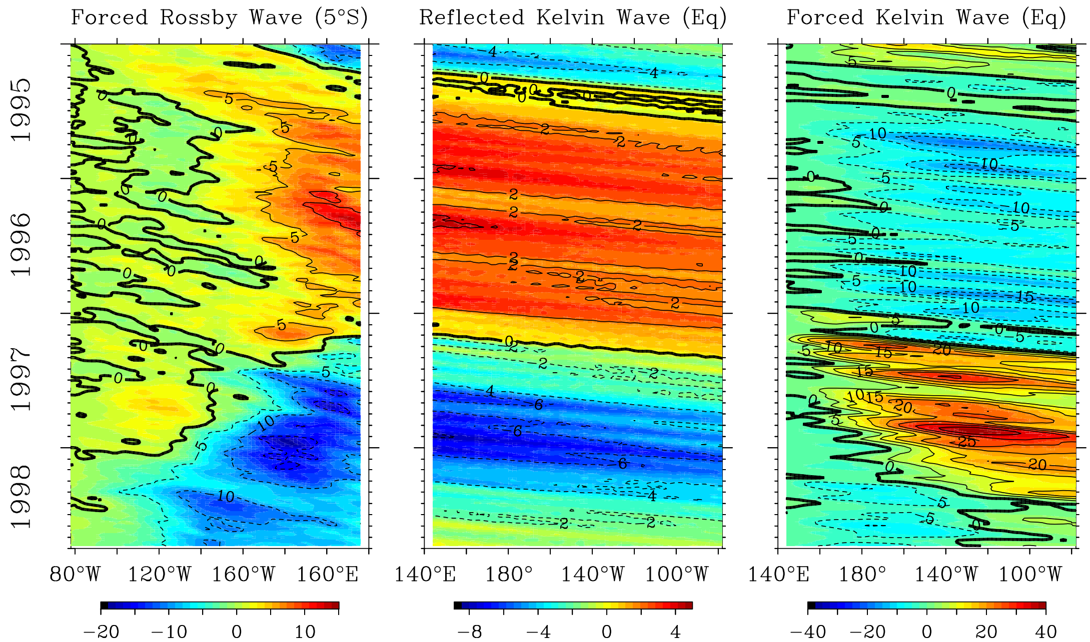

Figure 3. Simulated wind-forced Rossby wave sea level amplitude at 5°S (left), western boundary-generated Kelvin wave amplitude along the equator (middle), wind-forced Kelvin wave amplitude along the equator. The contour interval in the middle panel is 2 cm, whereas it is 5 cm for the two outer panels. Longitude axis for the Rossby wave panel has been flipped so that the interface between incident Rossby waves and reflected Kelvin waves at the western boundary is clear. Rossby wave amplitudes on the equator (for direct comparison with Kelvin wave amplitudes there) are about 50% of those at 5°S. In each case a mean seasonal cycle based on 1986–96 has been removed.

ber 1998 with daily wind stresses from the European Centre for Medium Range Forecasting (ECMWF), objectively corrected with moored buoy winds from the Tropical Atmosphere Ocean (TAO) Array [*McPhaden*, 1999]. Similar to *Yu and McPhaden* [1999], we use linear damping that is vertical mode number dependent, with a time scale of 12 months for the first vertical mode. The ocean basin spans 120°E to 80°E, with idealized straight north-south meridional boundaries and an assumed wave amplitude reflection efficiency of 80% at both eastern and western boundaries [*Clarke*, 1991; *Boulanger and Menkes*, 1999].

The model is validated primarily with sea level data from the TOPEX/Poseidon altimeter [*Fu et al.*, 1994]. Sea level is a proxy for heat content (Figure 2) since both vary primarily as a result of changes in thermocline depth. High sea level is generally associated with a deep thermocline and high heat content, and vice versa.

Both the model and TOPEX/Poseidon show low sea levels in the eastern Pacific and elevated sea levels in the western Pacific in 1995–96 (Figure 2). Both then show the large sea level rise in the east (20–30 cm) and large sea level depression in the west (10–20 cm) during 1997. Peak sea level elevations occurred in late 1997 in the eastern Pacific, after which positive anomalies diminished. At the same time, low sea level anomalies in the western Pacific migrated eastward along the equator.

The model affords an opportunity to diagnose in very simple terms the wave processes involved in evolution of the 1997–98 El Niño (Figure 3). Prior to the El Niño, sea level and heat content built up in the western Pacific due to downwelling Rossby waves associated with stronger than normal trade winds. These waves reflected off the western boundary as downwelling Kelvin waves in 1995 and 1996, consistent with the delayed oscillator theory. However, sea level amplitudes of the boundary-generated downwelling Kelvin waves were only about 2 cm, compared to 5–10 cm upwelling tendencies in 1995–96 due to directly wind-forced Kelvin waves. Moveover, boundary-generated Kelvin waves at the end of 1996 were dwarfed by MJO-forced downwelling Kelvin waves with 15–20 cm sea level amplitudes.

The model also indicates that upwelling Rossby waves initiated at the onset of El Niño in the western Pacific subsequently reflected into upwelling Kelvin waves at the western boundary. The 4–6 cm sea level amplitudes of these boundary-forced Kelvin waves contributed to the slow drop in sea level (and elevation in thermocline depth) along the equator in early 1998. However, beginning in early 1998 the appearance of easterly anomalies in the western Pacific, and westerly anomalies in the eastern Pacific (Figure 1), led to a comparable tendency for falling sea level and shoaling thermocline, with the easterlies forcing upwelling Kelvin waves and the westerlies forcing upwelling Rossby waves (Figures 2 and 3).

Consequently, maximum sea level depression (and thermocline shoaling) along the equator in mid-1998 occurred at the intersection of Kelvin and Rossby wave characteristics between about 125°W and 170°W (Figures 1 and 2. It was in this range of longitudes where the greatest SST cooling occurred following the return to near normal strength of the easterly trade winds at the end of the El Niño. The suddenness of this cooling was directly related to the shallowness of the thermocline resulting from equatorial wave processes.

4. Discussion

The equatorial Pacific was primed for an El Niño to occur in late 1996 due to the build up of heat content in the western equatorial Pacific over the previous 12–18 months. However, our results suggest that the rapid onset and ultimate strength of the 1997–98 El Niño may have been related to the onset of westerly winds associated with the MJO, which excited downwelling Kelvin waves an order of magnitude larger than those generated by western boundary reflections. The model is linear and so does not explicitly account for nonlinear ocean-atmosphere interactions and/or ocean dynamics required to rectify the intraseasonal MJO signals into lower frequency variations associated with ENSO. However these nonlinearities are explicitly contained in the observed winds which are used to force our model.

The MJO goes through a normal seasonal intensification every boreal winter and spring. In late 1996, though, it intensified even more. This unusual intensification may have been a random occurrence that just happened to coincide with a build up of heat content in the western Pacific in late 1996. On the other hand, unusually warm SSTs in the western Pacific, coincident with the Rossby wave-mediated heat content build up in 1995–96 (Figure 1) may have contributed to the initial amplification of the MJO as it passed over the western Pacific in late 1996–early 1997 [*Wang and Xie*, 1998]. In either case, MJO forcing could then have set in motion an ocean-atmosphere instability in which the western Pacific warm pool expanded eastward through zonal advection, and successive MJO-forced downwelling equatorial Kelvin waves grew in amplitude as westerly wind energy input into the ocean increased [e.g., *Kessler et al.,* 1995]. These events would have led to a further large-scale weakening of the tradewinds as the east-west SST gradient diminished in response to an eastward displacement of the western Pacific warm pool and reduced upwelling in the eastern Pacific.

All El Niños from the 1950s to the present have been associated with elevated levels of intraseasonal westerly surface wind forcing related to the MJO and other phenomena such as tropical cyclones [e.g., *Verbickas,* 1998, and references therein]. Recent theoretical studies indicate that such forcing can markedly alter the evolution of the ENSO cycle if it occurs on time and space scales to which the ocean is sensitive, and when background oceanic and atmospheric conditions are conducive to the rapid growth of random disturbances [*Moore and Kleeman*, 1999]. Thus, while it has been argued that episodic wind forcing is neither a necessary nor a sufficient condition for El Niños to occur, our analysis suggests that the MJO significantly contributed to the strength and abrupt onset of the 1997–98 El Niño.

At the height of the 1997–98 El Niño, easterly wind anomalies appeared in the far western Pacific, a feature noted in previous El Niños as well [*Weisberg and Wang*, 1997]. These easterly anomalies excited upwelling Kelvin waves in early 1998 of comparable magnitude to those generated at the western boundary. In addition, in early 1998 westerly wind anomalies appeared in the eastern Pacific, generating upwelling Rossby waves which elevated the thermocline as they propagated westward. These waves added to the upwelling tendencies produced by wind-forced and western boundary-generated Kelvin waves, the superposition of which led to maximum thermocline shoaling and SST cooling between about 125°W and 170°W in mid-1998.

In conclusion, our results shed light onto equatorial wave processes that were operative during the 1997–98 El Niño. However, the relative importance of physical processes that give rise to ENSO variations may vary from event to event, so we must be cautious in generalizing based on a single case study. *Picaut et al.* [1997], for example, suggested that eastern boundary-generated Rossby waves may be important in affecting the cyclic nature of ENSO. These waves, which are present in the TOPEX/Poseidon data and in our model results, were of secondary importance during the onset and termination phases of the 1997–98 El Niño [*Boulanger and Menkes*, 1999; *McPhaden*, 1999]. However, this conclusion should not be applied to all El Niños, and further research is required to better understand event-to-event similarities and differences.

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