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Evidence of an extratropical atmospheric influence during the onset of the 1997-98 El Niño

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Abstract. The major 1997-98 El Niño episode was initiated by a series of very energetic westerly wind bursts in late 1996 and early 1997. Downwelling oceanic Kelvin waves were subsequently generated and propagated rapidly eastward across the equatorial Pacific Ocean and induced significant warming in the eastern basin. By analyzing newly available wind products derived from SSM/I satellite observations, we found indications that these westerly wind bursts were embedded within the active phase of the tropical intraseasonal oscillation (the Madden-Julian Oscillation) but their amplitudes were greatly enhanced in the western Pacific sector. The local enhancement involved the development of equatorial twin cyclones which themselves were induced by northerly cold surges from East Asia/Western North Pacific into the tropical Pacific, demonstrating an extratropical atmospheric influence on tropical processes.

1. Introduction

The El Niño phenomenon refers to an anomalous sea surface warming in the central and eastern tropical Pacific Ocean and along South America. The related atmospheric change is called the Southern Oscillation, referring to the large-scale seesaw in atmospheric pressure between the south eastern tropical Pacific and the north of Australia (*Bjerknes* [1966]. El Niño - Southern Oscillation (ENSO) occurs at three-to-seven year intervals and lasts typically about 12 to 18 months. The year 1997 witnessed one of the greatest such events in the century. This event induced large-scale changes in tropical rainfall, wind patterns and air pressure, and had major impacts on weather conditions around the globe.

In the past few decades, tremendous progress has been made in understanding the dynamics of ENSO as a coupled phenomenon (*Rasmusson and Carpenter* [1982]). Leading ENSO theories based on equatorial wave dynamics and tropical air-sea coupling (*Philander et al.* [1984]; *Zebiak and Cane* [1987]; *Schopf and Suarez* [1988]; *Battisti* [1988]) seem to explain well how El Niño evolves once it has begun, but what governs the phase transition (i.e. the turnabout from a cold to a warm state or vice versa) is not fully understood. Studies of historical surface wind observations revealed that significant westerly wind bursts occurred over the western equatorial Pacific during the onset of some previous El Niño events (*Luther et al.* [1983]; *Harrison and Geise* [1991]). Since these westerlies can induce eastward-propagating downwelling equatorial Kelvin waves which lead to the South American coastal warming (*Busalacchi and O'Brien* [1980]), they have been suggested as the trigger. The 1997-98 El Niño is the best documented one to date thanks to multiple satellite global observing programs and the in situ mooring network. This enables a rather complete examination of how this El Niño started. In this study, data used for analyses include sea surface height (SSH) from the TOPEX/Poseidon altimeter, SST from the Reynolds analyses (*Reynolds and Smith* [1995]), outgoing longwave radiation (OLR) from the NOAA Climate Prediction Center, and oceanic subsurface information from Tropical-Ocean-Global-Atmosphere (TOGA) Tropical-Atmosphere-Ocean (TAO) arrays. We also used the six-hourly surface wind products derived from a blend of wind speed observations from the Defense Mapping Satellite Program Special Sensor Microwave Imager (SSM/I), ship and buoy observations, and surface wind analyses from the European Center for Medium Range Weather Forecasts (ECMWF) (*Atlas et al.* [1993]). In the following, we present evidence of the connection between westerly events and the onset of the 1997-98 El Niño and a possible link with extratropical anomalous winds.

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2. Tropical Atmosphere-Ocean Conditions during the Onset of the 1997-98 El Niño

The oceanic conditions across the whole equatorial Pacific were dramatically different between 1996 and 1997 (Figure 1). During 1996 SST and SSH were higher in the region west of the dateline and lower in the east basin in response to atmospheric perturbations. Westward trade winds over the central and western tropical Pacific were persistently stronger than average before January 1997 (Figure 2). This pre-onset condition, which had persisted since early 1995, reversed abruptly at the end of 1996, resulting in an eastward extension of the region of high SSH anomaly. The SSH anomaly, a short-lived signal as seen in Figure 1b, propagated rapidly along the equator and reached the South American coast in February 1997. One month later, another SSH anomaly with a greater amplitude developed near the western boundary and also subsequently propagated eastward. These eastward propagating Kelvin waves were also apparent at depth in modulations of the thermocline. Here, they are shown in the depth of the 20°C isotherm (Figure 1c), a commonly used index for thermocline variations in the tropical oceans. With the subsequent arrival of the second group of Kelvin waves in April and May, the thermocline in the east was greatly depressed and the sea surface warming in the eastern basin became extensive. It is quite apparent

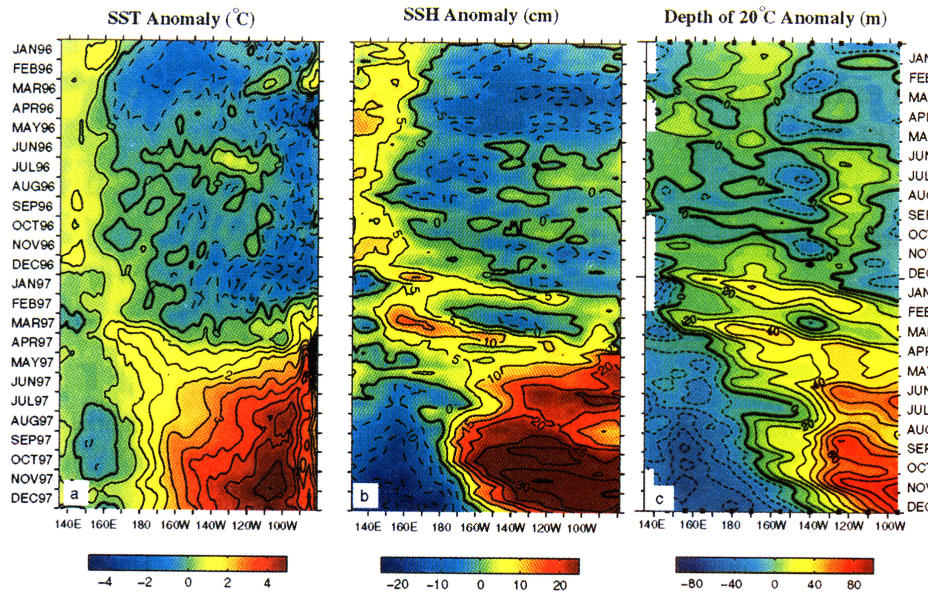

Figure 1. Time-longitude sections (2°S - 2°N) of anomalous (a) SST from the Reynolds analyses (weekly average), (b) SSH from TOPEX/Poseidon altimeter (10-day average), and (c) depth of 20°C isotherm (5-day average) derived from TOGA/TAO moorings. Anomalies in (a) are departures from the 1982-1992 base period weekly means. Anomalies in (b) are deviations from a monthly-mean surface composed from T/P data spanning from 1993-1996. Anomalies in (c) are relative to monthly climatologies linearly interpolated onto 5-day intervals.

that the two groups of downwelling Kelvin waves played a key role for the onset of the current El Niño episode. It is known that Kelvin waves are generated either directly by wind-stress forcing or result from the reflection of Rossby waves at the western boundary. As seen from Figure 2a, these downwelling Kelvin waves were generated at a time of westerlies over the western and central Pacific, with the first major episode occurring in late December 1996 and the second in late February 1997. These sudden changes in the wind fields were also recorded by the NSCAT satellite sensor and TOGA TAO moorings (not shown). Therefore a key issue for understanding the onset mechanism for the 1997-98 El Niño is the identification of the cause of westerly wind bursts.

The focus of this report is on the onset phase and so only westerlies that occurred before May 1997 are discussed in the following. Each wind burst excites a Kelvin wave pulse. Though sometimes feeble, these waves can be clearly identified (Figures 1b, c) as eastward propagating signals. The amplitudes of downwelling Kelvin wave packets are clearly related to the strength and duration of westerlies as well as their spatial extent. During the winter of 1995-96 westerly events were not frequent. A few episodes appeared (for example, in February 1996) and they were generally weak. However, during September 1996 to March 1997 westerly anomalies occurred almost every month over the western Pacific. The episodes in late December 1996 and in late February 1997 were particularly intense and longer-lived. The quasi-periodic occurrence of the westerly anomalies at about every 30-40 days during this period suggests a possible connection to the tropical intraseasonal variations, namely the Madden-Julian Oscillation (MJO) (*Madden and Julian* [1972]). Indeed, the time series of the satellite-derived Outgoing Longwave Radiation (OLR) (an indicator of atmospheric convective activity) in the tropical sector (Figure 2b) indicate clearly that these westerly anomalies were ac-

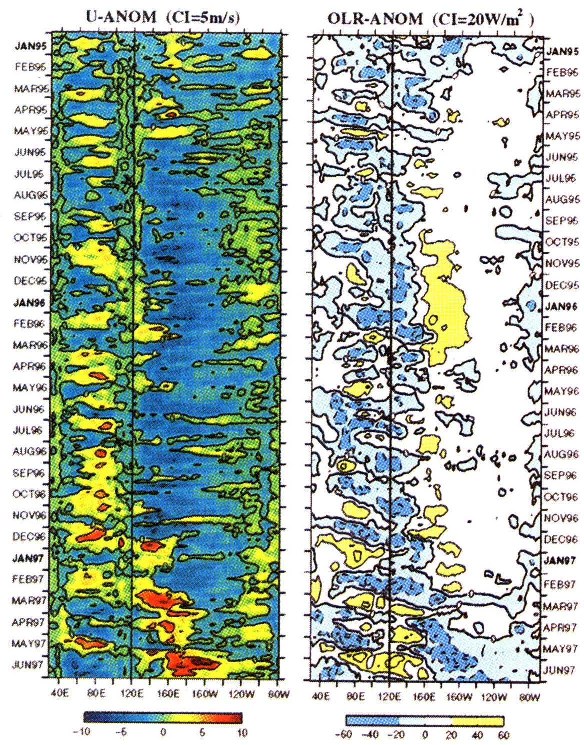

Figure 2. (a) Time-longitude section (2°S - 2°N) of anomalous surface winds (m/sec) derived from SSM/I data. Anomalies are departures from the monthly means (1988-1996) linearly interpolated onto weekly intervals. (b) Time-longitude section (5°S - 5°N) of anomalous outgoing long-wave radiation (OLR). Blue colors indicate enhanced convective activity. Anomalies are departures from the 1979-1995 base period pentad means. A three-point running average is applied in time.

companied by eastward propagating, large-scale convective anomalies and so were associated with the MJO.

Observed intraseasonal Kelvin waves (30-90 days) in the equatorial Pacific Ocean have been attributed to the direct atmospheric forcing associated with the MJO (e.g., *Kessler et al.* [1995]). The role of such intraseasonal atmosphere/ocean variability in the development of interannual El Niño events has also been previously examined (e.g., *Lau and Chan* [1988]). The close association between the MJO and the two very energetic westerly wind bursts that likely triggered the 1997-98 Niño event seems to substantiate some MJO-ENSO relationship; however, as *Kessler et al.* [1995] point out, the MJO itself appears to be insufficient to initiate El Niño. This is clear for the 1997-98 event: despite the ocean being preconditioned with positive SST and SSH anomalies in the western Pacific and the MJO being active during January-April 1996, no El Niño occurred. It is possible that the phase of intraseasonal variability is important in the MJO-ENSO interaction. The westerly wind events in the western Pacific were not active during the entire 1995-96 period, although the MJO signals in the Indian Ocean were stronger in 1996 than in 1995 (Figures 2a, b). Once having propagated to the Pacific sector, the MJO signals weakened and were confined to the west of 160°E. This is perhaps related to the SST modulation of the MJO, since during that time the warm SST anomalies were confined to west of 160°W and the cold anomalies to the east (Figure 1a). The strong westerly wind bursts over the western Pacific in late 1996 were clearly associated with the MJO signal, but the magnitude of that signal diminished to less than 2 m/s as the anomaly crossed the maritime continent and reached the western Pacific. The intensification (to speeds over 9 m/s) appears to be confined to the Pacific sector and occurred so suddenly that the MJO was unlikely the direct and sole cause. In the following, we present analyses to show that the enhancement of the two westerly wind bursts was influenced by anomalies in the extratropical atmospheric circulation, the so-called cold surges of northerly wind anomalies from East Asia/Western North Pacific into the tropical Pacific with a period of 1-5 days (*Lau et al.* [1983]).

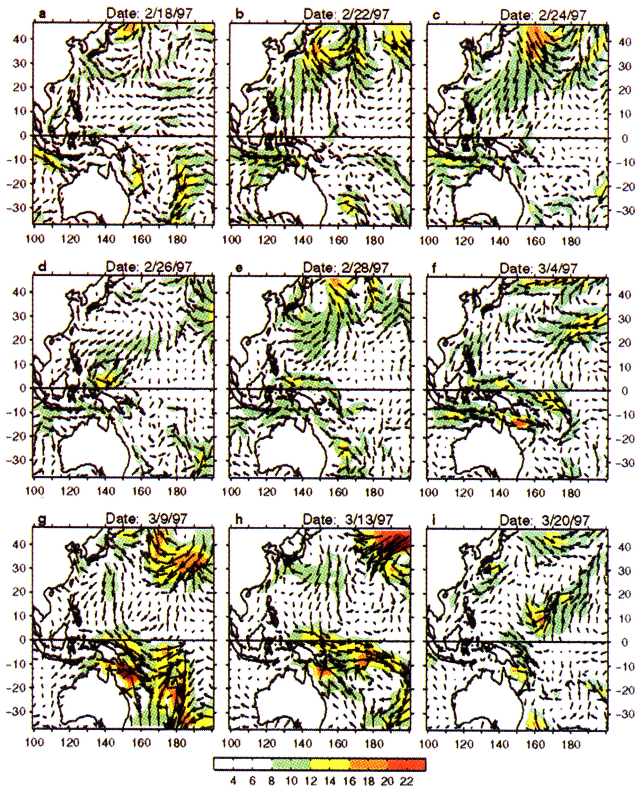

Figure 4. **Evolution of daily-averaged anomalous surface winds derived from SSM/I in February-March 1997. Wind speeds greater than 8 /s are shaded.**

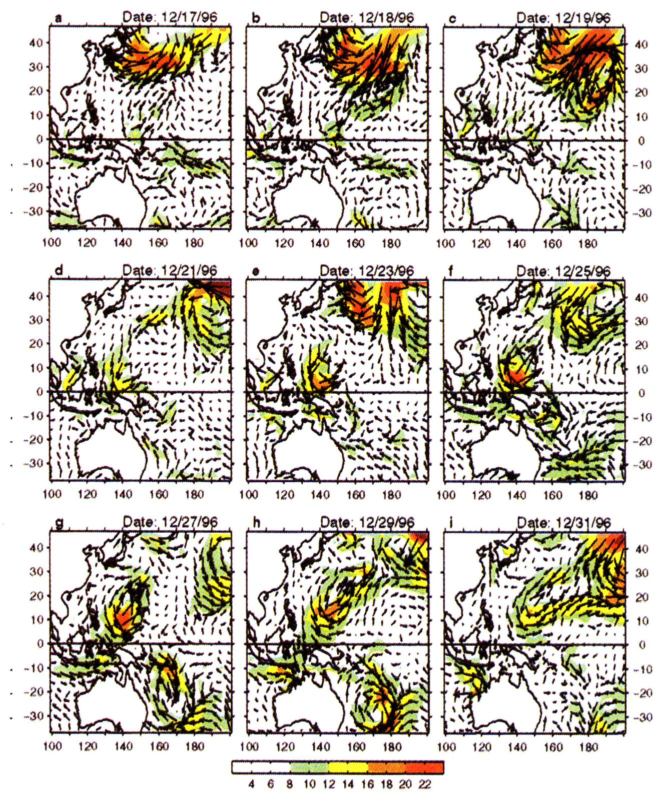

Figure 3. Evolution of daily-averaged anomalous surface winds derived from SSM/I in December 1996. Anomalies are calculated relative to the seasonal cycle. Wind speeds greater than 8 /s are shaded.

3. Influence of Extratropical Atmospheric Disturbances

The evolution of daily-averaged surface wind anomalies over the western Pacific Ocean in December 1996 and February-March 1997 are shown in Figures 3 and 4. It is interesting to note the connections between the equatorial eastward propagating MJO signal, the mid-latitude air intrusion, the development of tropical cyclones, and the subsequent enhancement of westerly wind events. In mid December 1996 (e.g. Figure 3a), the westerly wind anomalies associated with the MJO propagated into the Pacific sector (the branch located between 10°S and the equator). On December 18 (Figure 3b), a northerly surge, originating north of 30°N over the East China Sea, started to penetrate deep into the equatorial region between 120 and 140°E. As the surge continued for the next 4 days (e.g. Figures 3c, d), the weak cyclone which had been barely visible just north of the equator at 150°E as of December 17 strengthened significantly. A full cyclone was developed by December 23 (Figure 3e). The resultant equatorial westerly wind burst between 130 and 150°E excited the Kelvin wave packets evident at this time in Figure 1. Meanwhile, a cyclone centered near 160°E was being formed in the Southern Hemisphere under the influence of cross-equatorial winds, the MJO, and a westerly wind surge from the Indian Ocean along 10°S (Figure 3f). By December 27, this cyclone was fully established and a cyclone pair straddling the equator was clearly seen. The association of westerly wind bursts with cyclone pairs has been documented in previous studies (*Keen* [1982]). However, in this case the Southern Hemisphere cyclone, due to its distance from the equator and the short duration, seemed to have limited influence on the westerly wind anomalies directly along the equator. After December 27, both cyclones propagated eastward and poleward, and the westerly wind burst decayed (Figures 3h-i).

The enhancement of the MJO-associated westerly wind event in February-March 1997 also involved surges from the mid-latitudes but the development was somewhat more complex. The mid-latitude surge over the East China Sea began on February 18 in the region between 120 and 140°E (Figure 4a). By February 22, a weak cyclone north of the equator began to form at the tip of the air stream (Figure 4b), and it was intensified greatly during the next 4 days (Figures 4c-e). In the meantime, the northerly surge propagated eastward, faster in the mid-latitudes than in the tropics. Because of this propagation, the cyclone dissipated, but the zonal winds along the equator strengthened and extended zonally to 160°E (Figure 4e). Another northerly surge struck the region between 120° and 140°E in early March (Figure 4f) and subsequently propagated through the region in a similar manner. The strongest influence of the northerly surges moved eastward over time. This, however, was not the only reason that the extent of the westerly wind burst moved eastward during March. The cyclone that formed in the Southern Hemisphere on March 4 under the influence of cross-equatorial winds and anomalous flow from the Indian Ocean at 10°S was closer to the equator for this event than that in December. It was centered at about 175°E and extended the region of anomalous westerlies to near the dateline. This cyclone propagated southward over the following several days and meanwhile diminished its influence on the equatorial anomalies. The combination of equatorward surges in both hemispheres prolonged this westerly wind anomaly until March 20 (Figure 4i). At that time it was weak (less than 5 m/s) and was limited to west of 155°E.

The preceding discussions indicate that the background for the westerly wind events in the western Pacific was set by the MJO and that the enhancement process was largely triggered by the northerly cold surges. It should be noted that the MJO itself can often induce equatorial cyclones. Indeed, in late December 1996 a weak cyclone was present right before the outburst of cold surges (Figure 3a). However, the MJO did not bring any clear cyclonic structures into the northern western tropical Pacific at the onset of the episode in February-March 1997. It seems that the MJO-related cyclones are not necessarily a precondition for the cold surge-related cyclone development.

4. Discussion

It appears from observations that the penetration of mid-latitude surges into the western equatorial Pacific played a key role in developing the westerly wind bursts that directly preceded and may have triggered the current El Niño. The mid-latitude intrusions coinciding with the passage of the MJO over the western tropical Pacific induced tropical cyclone development in the western Pacific and enhanced the MJO-associated westerly wind events. Interestingly, a westerly wind burst in February 1996 also involved a cold surge from the mid-latitudes. However, the extratropical-tropical interaction did not generate a westerly anomaly of sufficient magnitude to force a Kelvin wave to disturb the eastern equatorial Pacific. Questions remain as to the distinct role of the MJO in ENSO variability and the chaotic nature of the phasing of these interactions. A satisfactory answer to these questions may also provide a key to other related issues such as why ENSO is phase-locked to the annual cycle and what causes the aperiodicity.

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