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Roles of Multi-Scale Disturbances over the Tropical North Pacific in the Turnabout of 1997–98 El Niño

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ABSTRACT

The space-time features of major vorticity disturbances over the western North Pacific during the 1997–98 El Niño ranked as one of the strongest events on record was investigated in this study. We distinguished the different roles that these disturbances had on different timescales in causing the reversal or turnabout of the El Niño event. Remarkable differences in the various disturbances of synoptic, intraseasonal, and interannual timescales were found in the time evolution, propagation, and in their contributions to the changes in near-equatorial zonal flow, which was crucial to the demise of the warm sea surface temperature anomalies in the central-eastern Pacific. It is hypothesized that the westward-traveling synoptic and intraseasonal oscillations in the western North Pacific might be considered as a self-provided negative feedback from the El Niño and played an additional role in its reversal in comparison with other interannual internal and external forcings. In this case, the off-equatorial synoptic and intraseaonal fluctuations served as a stochastic forcing for the tropical ocean and gave rise to the aperiodicity or irregularity of the El Niño-Southern Oscillation.

Key words: intraseasonal oscillation, ENSO, Kelvin wave, western North Pacific

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1. Introduction

Low-level wind anomalies over the western tropical Pacific play a crucial role in triggering the phase transitions of the El Niño-Southern Oscillation (ENSO). These wind anomalies excited the equatorial oceanic Kelvin waves (McPhaden, 1999; Boulanger and Menkers, 2001; McPhaden, 2004), of which the large cumulative effects were comparable with the well-known western-boundary wave reflection that serves as a delayed negative feedback to the maintenance of the ENSO cycle (Weisberg and Wang, 1997; McPhaden and Yu, 1999; Wang et al., 1999). An anomalous, large-scale, anti-cyclonic circulation over the Philippine Sea (PSAC), which usually is established approximately one season prior than the mature phase of the El Niño and persists into the subsequent summer (Zhang et al., 1996; Wang and Zhang, 2002), is responsible for the predominance of the easterly anomalies over the western Pacific warm pool before the turnabout of the El Niño (Wang et al., 1999). Recently, Vecchi and Harrison (2006) and Vecchi (2006) suggested that the termination of the 1997–98 El Niño was due to changes in the meridional structure of the zonal wind field, e.g., a southward shift in the near-date-line zonal wind anomalies in November 1997, which drove eastward propagating thermocline shoaling. Those phenomena reflect the influence of the anomalous off-equatorial atmospheric circulation on the near-equatorial ocean-atmosphere coupling processes in the Pacific.

For the origin of the PSAC, Watanabe and Jin (2002) noticed the role of the Indian Ocean warming and the Tibetan Plateau in its formation. Wang and Zhang (2002) emphasized the combined effects of the remote forcing of the El Niño-related warm sea surface temperature (SST) anomalies in the eastern-central Pacific, the tropical-extratropical interaction and in the monsoon-ocean interaction. More recently, a mechanism based on seasonally-dependent, moist,

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static-energy advection has been proposed in an effort to interpret the onset of the PSAC and its eastward movement from South Asia (Chou, 2004). Modeling studies (e.g., Lau and Nath, 2006) emphasize the influence of negative vorticity tendencies over the subtropical northwestern Pacific, which arise from the advective process of the El Niño-induced North Pacific cyclonic circulation.

The aforementioned interpretations mainly focused on the slowly-varying process of the PSAC that is associated with the seasonal-interannual variability of the near-equatorial wind anomaly. Observational evidence suggests that the onset of El Niño is significantly modulated by higher frequency variabilities, such as the Madden-Julian Oscillation (MJO) and the westerly wind bursts over the warm pool region (McPhaden, 1999; Li and Long, 2001; Belamari et al., 2003; Boulanger et al., 2004). A great deal of endeavors have been made in an effort to link the activity of the MJO with ENSO, but generally only a weak statistical correlation could be found between the two phenomena (Hendon et al., 1999; Slingo et al., 1999). More recently, the role of the eastward-propagating MJO in the onset of El Niño has been more and more recognized as a stochastic forcing that not only introduces the irregularity of the ENSO, but also acts to sustain the ENSO cycle (e.g., Roulston and Neelin, 2000; Zavala-Garay et al., 2003; Batstone and Hendon, 2005).

In contrast, little attention has been paid to the role of high frequency variabilities on the turnabout of El Niño or in the onset of La Niña. Evidence has shown that the occurrence of El Niño may significantly suppress the activity of the MJO in the western Pacific (Kessler et al., 1995; Chen et al., 2001; Lau, 2005). This feature implies that the eastward-traveling MJO, during a warm episode, may contribute very little to the onset of equatorial easterlies in the western Pacific and thus, to the turnabout of El Niño. In fact, there exists an active synoptic scale (Liebmann and Hendon, 1990) and intraseasonal scale oscillation (ISO) in the western North Pacific (Murakami et al., 1984; Lau and Chan, 1986), both of which are characterized by a westward propagation and notable seasonal-preference (Lau and Lau, 1990; Gu and Zhang, 2002; Teng and Wang, 2003; Li and Wang, 2005). Those westward-traveling fluctuations tend to be enhanced during an El Niño episode (Wang and Zhang, 2002; Teng and Wang, 2003; Ren and Huang, 2003; Lu and Ren, 2005). This feature motivated us to explore their potential connection with the occurrences of zonal wind anomalies during the mature phase of El Niño and to further examine their contribution to the phase transition of ENSO. One of the strongest warm and the best-observed events in history was recorded during the 1997–98 El Niño, which provided us with a strong case to validate our deduction.

In this study, we first identified the dominant atmospheric modes that occurred during the period between 1997 and 1998, then demonstrated their distinct spatial-temporal characteristics, finally clarified their different roles in the regime shift of the 1997–98 El Niño event. This paper is organized as follows: Section 2 briefly presents the data and methods used for this study. Section 3 describes the temporal evolution and spatial structure of the multi-scale fluctuations in the lower troposphere in the western North Pacific. Section 4 focuses on the contributions of those fluctuations to the turnabout of the 1997–98 El Niño through the associated changes in the near-equatorial zonal-wind anomalies. Next, we propose a hypothesis on the self-provided negative feedback process of the warm events to the El Niño reversal in section 5. The paper concludes in section 6 with a summary and discussion.

2. Data and method

The daily and monthly horizontal winds at 1000-hPa used in this study was provided by the National Centers for Environmental Prediction-National Center for Atmospheric Research reanalysis (Kalnay et al., 1996). Wavelet analysis was applied to determine the major modes of the vorticity variability and to understand how these modes varied with time. To test the significance of the local wavelet spectrum, we performed Monte Carlo simulations using a colored noise process with a lag-1 coefficient of 0.72. A detailed description of this analysis tool can be found in Torrence and Compo (1998). The dominant space-time characteristics of the vorticity disturbances that were significant on the specific timescales, were investigated by using an extended empirical orthogonal function (EEOF) technique, which was capable of depicting propagating modes. More information about this tool can be found in Weare and Nasstrom (1982). In addition, the daily depth of 20°C isotherm provided by the Tropical Atmosphere and Ocean project (TAO) was used to represent the vertical shift in the thermocline in the equatorial Pacific Ocean during the 1997–98 El Niño event.

3. Spatial and temporal features of multi-scale fluctuations in the western North Pacific

Figure 1 shows the Hovmöller diagram depicting the daily vorticity anomalies averaged over the 5°–

20°N latitude band. Unless otherwise specified, all variables discussed hereafter are the averages within these latitudes. During the second half of 1997, cyclonic disturbances prevailed over all longitudes and traveled westward from the central-eastern Pacific. The most striking change in this pattern occurred near the end of 1997, when the El Niño reached its mature phase (McPhaden, 1999). This westward-propagating behavior abruptly vanished afterwards, coherent with the positive anomalies that significantly weakened and retreated to the central-eastern Pacific. In the meantime, the western North Pacific was dominated by anomalous anti-cyclonic disturbances. This feature remained almost unchanged in the first half of 1998, except for a renewal of the westward propagation of some of the weaker disturbances that occurred in the early summer.

To identify the major periodicities of vorticity variability, we show in Fig. 2 the distribution of the wavelet power spectrum at 170°E, which reflects the basic features of the spectral distributions of the grid points from 120°E to the dateline. Note that we carried out the analysis for one grid, instead of providing regional means, because the spatial average readily smoothes out small-scale disturbances. Three significant peaks in the power spectra were found on the following timescales: 4–14 d (synoptic, hereafter SO), 20–60 d (intraseasonal, hereafter ISO), and annual-interannual (LFO). These modes showed different temporal evolutions. Coincident with the sudden disappearance of westward traveling disturbances shown in Fig. 1, the SO and ISO were active between the spring and the end of 1997 and then sharply weakened during the beginning of 1998. Such a depressed regime persisted into the fall of 1998. The scenarios of these modes in 1997–98 were generally consistent with the long-tem statistical results of Teng and Wang (2003), which showed the enhancement of 15–40 d and 8–10 d fluctuations between July and October during the development year of El Niño due to the ENSO-produced change in the mean circulation. In contrast, the LFO remained robust throughout 1997 and 1998.

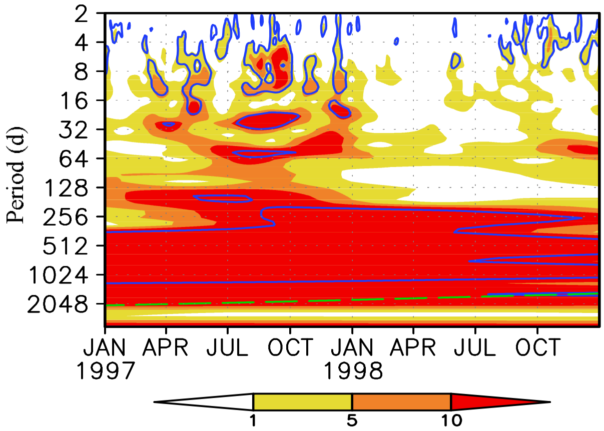

Fig. 2. Wavelet power spectrum of the daily 5°–20°N mean-vorticity anomalies at 170°E. The thick blue contours enclose the regions of greater than 95% confidence for a red-noise process with a lag-1 coefficient of 0.72. The green, dashed line indicates the "cone of influence" where the edge effect becomes important. Only a portion of the total analysis period (1989–2004) is shown in the figure.

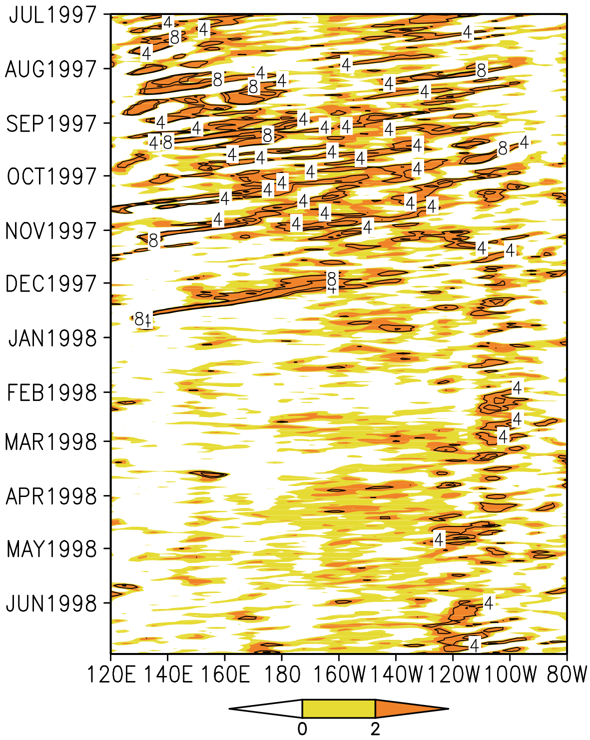

Fig. 1. Hovmäller diagram of 1000-hPa daily vorticity anomalies (10^{-6} s^{-1}) averaged over 5°–20°N latitude band. The positive values are shaded.

Furthermore, we used band-pass filters to isolate the disturbances on the different timescales, from the daily-mean series for SO and ISO to the monthly-mean data for LFO. The corresponding filter for SO (ISO) had a full response of 8 (35) d and half-power points of 4 (20) d and 16 (61) d. The full response of the filter for LFO was set to 40 months, with the half power points at 20 months and 80 months. Figure 3 illustrates the first EEOF modes of these three filtered components. The SO was characteristic of the westward traveling fluctuations, reaching their maximum over the western Pacific. Lau and Lau (1990) have provided a detailed description of the structure and

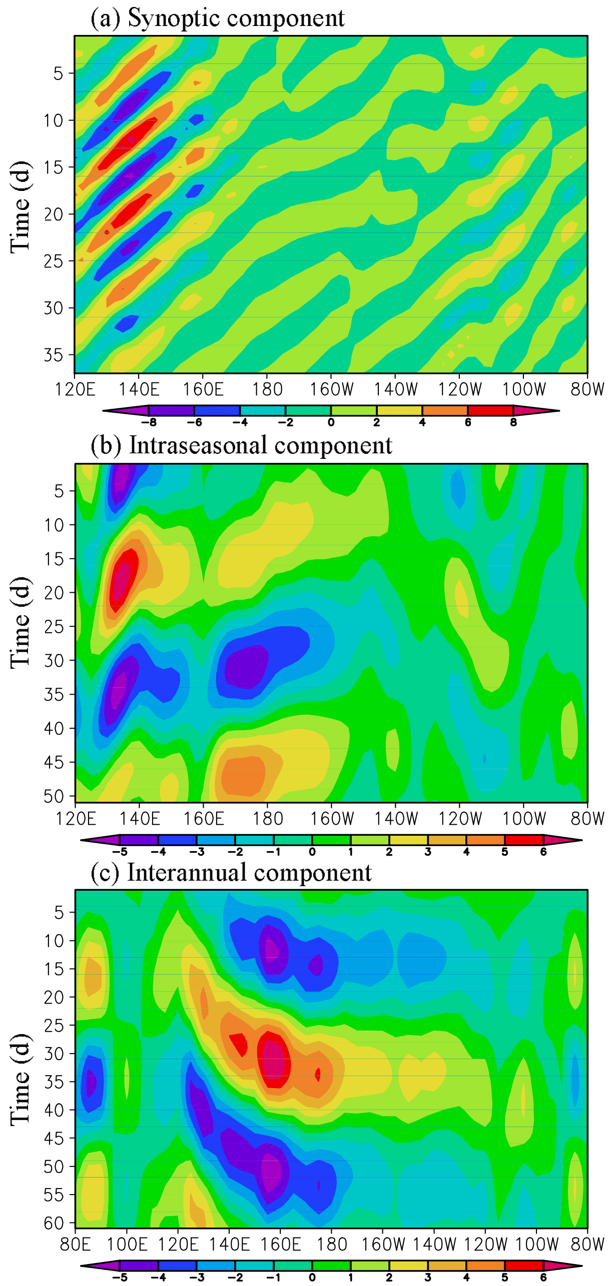

Fig. 3. The first EEOF mode of (a) synoptic, (b) intraseasonal and (c) interannual timescale vorticity fluctuations in the 5°–20°N latitude band.

propagation of the SO and have attributed its geographical dependence to the changes in the mean atmospheric conditions in which the disturbances are embedded. The ISO exhibited a different spatial structure from SO. It originated near 160°–140°W, and then diverged to the west and east simultaneously, with the westward branch moving faster than the eastward branch. Both branches enhanced gradually during their movements, with the fastest growth rate occurring over the western Pacific warm pool. It is believed that the ISO, in comparison to the MJO, which is usually produced in the tropical Indian Ocean and travels eastward towards the western Pacific Ocean, is a manifest of the atmospheric response to the SST forcing in the equatorial central Pacific (Wang and Xie, 1997), which are the moist, Rossby wave for the westward branch and the Kelvin wave for the eastward branch. For LFO, positive (negative) vorticity disturbances first emerged in 100°–120°E, then shifted towards the western Pacific and finally expanded into the central-eastern Pacific (see Fig. 3c). According to Wang and Zhang (2002), the establishment of the cyclonic (anti-cyclonic) circulation anomalies was due mainly to the Rossby response to the enhanced (suppressed) convection over the tropical western Pacific that was associated with ENSO. Chou (2004) has applied the anomalous horizontal advection of the moist static energy to explain the eastward movement of the vorticity anomalies.

4. Role of the multi-scale disturbances in the turnabout of 1997–98 El Niño

According to McPhaden et al. (1998), one of the most significant advancements made for understanding ENSO that was achieved in last decade, was the accomplishment of the Tropical Atmosphere-Ocean array of moored buoys in the Pacific under the framework of the Tropical Ocean-Global Atmosphere observing system (TOGA). The abundant data that are collected by TOGA-TAO allowed us to explore the evolution of 1997–98 ENSO phase transition quite well. Figure 4 shows the temporal variations in the sea temperature anomaly profiles from the surface down to a 500 meter depth in the equatorial Pacific. The cold water in the mixed layer was mainly confined to the region west of the dateline in September 1997, but two months later it had expanded eastward and had extended to 150°W. In January 1998, the traveling cold water had reached into the eastern Pacific, with a minimum occurring at the depth of the thermocline. The deepening equatorial thermocline led to the decay of the matured El Niño in the succeeding several months.

To understand the subsurface processes for the ENSO transition shown above more clearly, Fig. 5 displays the Hovmöller diagram of the ISO component of the daily 20°C isotherm depth in the equatorial (2°S–2°N mean) Pacific Ocean. The ISO fluctuations in the thermocline depth became stronger and more active during the period between September 1997 and January 1998, than they did afterwards, which is similar to the evolution of the atmospheric ISO activities that are depicted in Fig. 1 and Fig. 2. Three significant

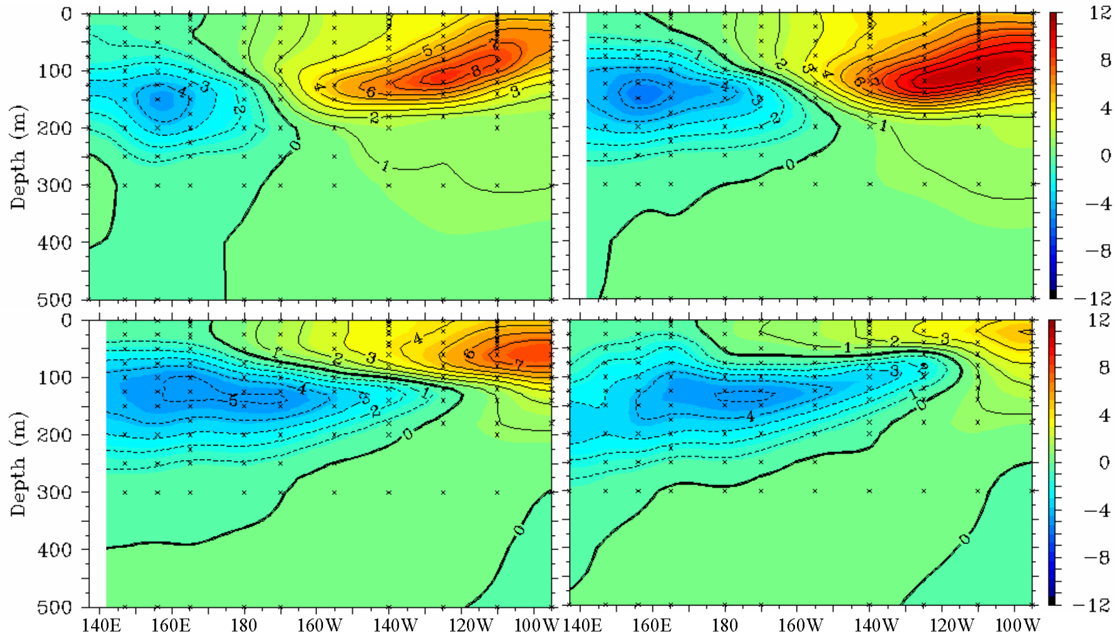

Fig. 4. Evolution in vertical profiles of the 2°S–2°N mean sea temperature anomalies as detected by the TOGA–TAO. These figures are derived by the TOGA–TAO online display system.

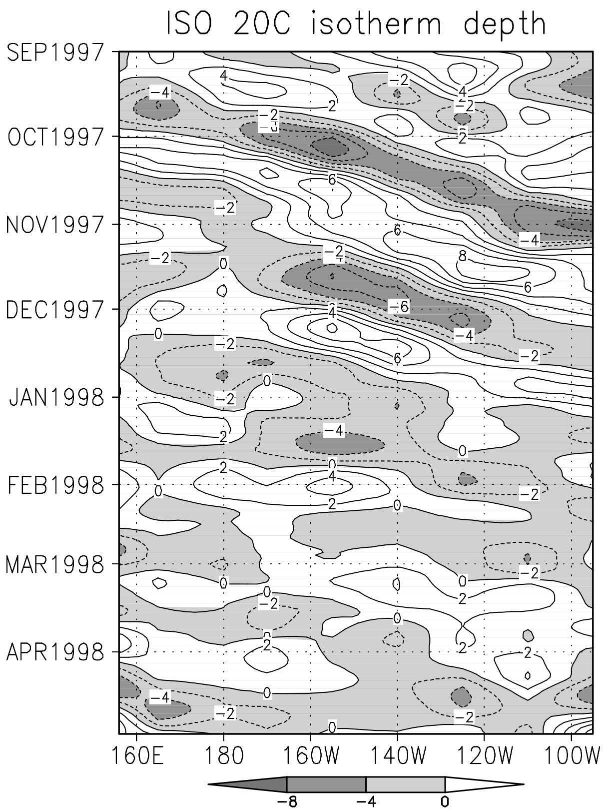

Fig. 5. Hovmäller diagram of the ISO component of the daily 20°C isotherm depth (unit: m) in the equatorial (2°S–2°N mean) Pacific Ocean.

episodes for the negative ISO thermocline depth can be identified. The first one started in the western Pacific in mid-September and reached into the eastern Pacific in early November 1997. The second and the third were driven in a similar way, but in mid-October and late December, respectively. Both were greatly enhanced in the central Pacific Ocean one month later. We also noticed positive ISO episodes for thermocline depth among those negative episodes, which worked as an adverse contribution to the demise of El Niño and may be overweighed by other components in thermocline depth variation.

As mentioned in the introduction, it has been well realized that the traveling cold water along the tilted thermocline as in Fig. 4 or the traveling fluctuations in thermocline depth that are shown in Fig. 5, actually arise from the upwelling Kelvin wave, which can be induced either by an easterly wind or by the western boundary reflection of a Rossby wave. Next, our efforts were made mainly to investigate the potential influences of off-equatorial, high- and low-frequency disturbances, which were revealed in section 3, on the variations of the near-equatorial easterly winds during the turnabout of El Niño.

Figure 6 shows the evolution of the 5°S–5°N mean zonal-wind anomalies, the corresponding 0°–5°N mean SO and ISO, along with the LFO components. All of the values were averaged over 137.5°–142.5°E, where easterly anomalies, as shown in Fig. 7a, tend to reach their minima. From September 1997 to January 1998,

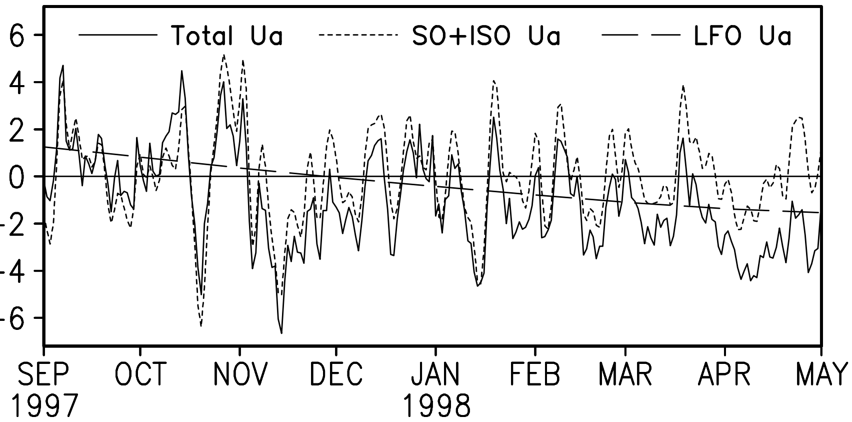

Fig. 6. Time evolution of the 5°S–5°N mean zonal-wind anomalies and their corresponding SO and ISO, along with the LFO components over the region between 0°–5°N. All of the values are averaged over 137.5°–142.5°E. Units: m s^{-1}.

it was remarkable that the easterly anomalies of the near-equatorial total zonal wind primarily came from the SO and ISO fluctuations north of the equator. After that, the SO and ISO components decreased in amplitude. On the other hand, the LFO component shifted from the original westerly phase to an easterly phase in December 1997 and then intensified with time. Afterwards, the total zonal-wind anomalies were dominated by the LFO easterly component. This feature suggests that the variations of equatorial zonal wind originated mainly from the SO and ISO components prior to February 1998 and from the LFO component afterwards.

As a further attempt to understand the roles of the off-equatorial SO and ISO disturbances in the occurrences of the near-equatorial easterlies during the period of late 1997 to early 1998, we examined the combined evolution of their 5°–20°N mean filtered components of vorticity (contours) and the evolution of the unfiltered zonal-wind anomalies (shaded) over 0°–5°N (Fig. 7a). Before the end of 1997, notable cyclonic (anti-cyclonic) disturbances surged from the central Pacific to the far western Pacific, coinciding with the westward-propagating westerly (easterly) anomalies in the near-equatorial band. Particularly, five periods of strong easterly anomalies, each accompanied by a remarkable anti-cyclonic fluctuation, were observed from October 1997 to January 1998. The combined SO and ISO easterlies within the region between the equator and the 5°N band (see the arrows in Fig. 7a), which induced the negative ISO fluctuations in thermocline depth in Fig. 5, accounted for most of those easterly variabilities. This indicates the dominance of the off-equatorial SO and ISO disturbances in the variations of the zonal-wind anomalies over the near-equatorial western Pacific. On the contrary, the LFO anti-cyclonic disturbance (negative value in Fig. 7b), which are usually accompanied by near-equatorial easterly anomalies, was relatively weaker and was mainly confined to the region west of 140°E during this period of time. The strong near-equatorial easterlies, together with the wave reflection in the western boundary of the Pacific and some other extraneous forcing, induced strong upwelling Kelvin waves, which eventually led to the decay of the El Niño (McPhaden, 1999; McPhaden and Yu, 1999). Since early 1998, both the SO and ISO weakened significantly and then retreated to the region west of the dateline, coherent with the eastward extension of the negative LFO vorticity towards the dateline. The behavior of the LFO matches well with the similar eastward expansion of the easterlies presented in Fig. 7a, which, thus, sets the precondition for the onset of the La Niña event that occurred in 1998.

5. Hypothesis: self-provided negative process of El Niño

Wang and Xie (1996) suggested that the westward-propagating SO and ISO discussed above are of Rossby-wave characteristic, which is modulated by the vertical shear of zonal-mean circulation. To verify the origin of the SO and ISO in the western North Pacific, during the period between late 1997 to early 1998, we display in Fig. 8 the evolution of 5°–20°N mean zonal-wind vertical shear (U_{850}–U_{200}) (shaded) and their anomalies (contour). As shown in Fig. 2, the ISO in 1997 appeared to be most prominent between July and October, when the mean circulation over the western North Pacific was featured by an easterly vertical-wind shear (increasing easterly wind with height, see Fig. 8). Such a feature is also consistent

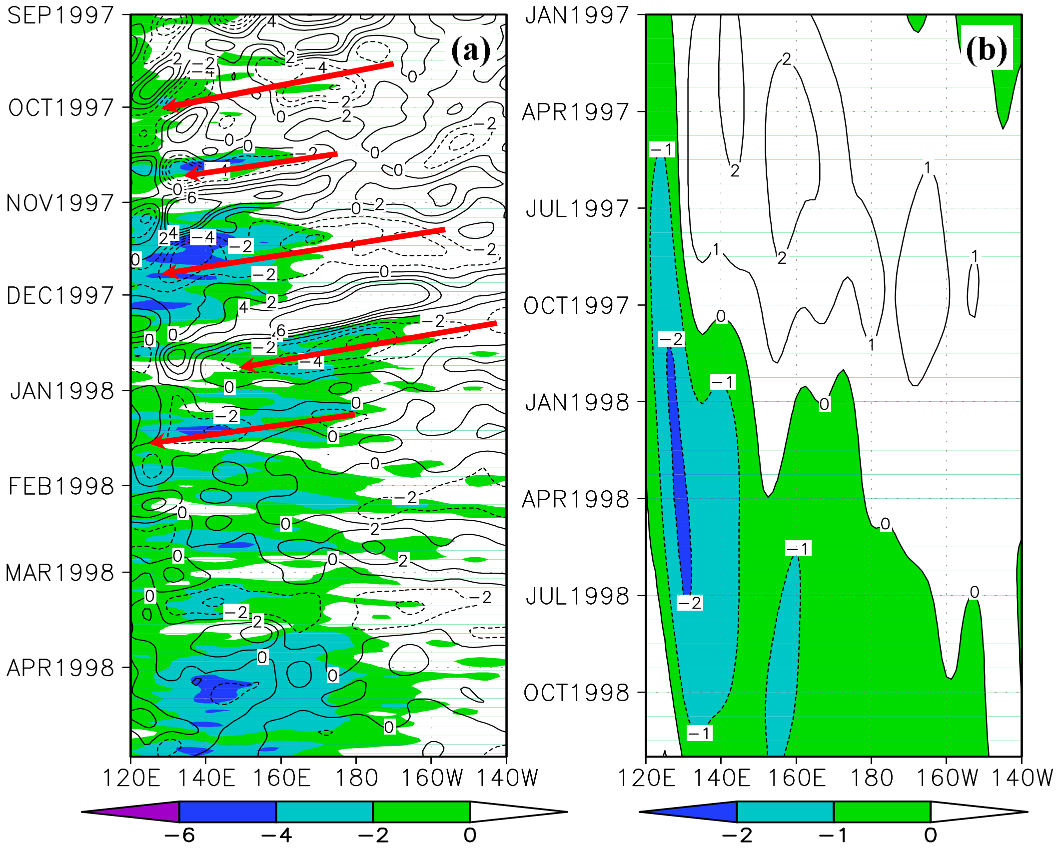

Fig. 7. (a) Left panel: Hovmöller diagram of the filtered synoptic and intraseasonal vorticity fluctuations (10^{-6} s^{-1}, contours; 5°–20°N) and unfiltered monthly zonal-wind anomalies (m s^{-1}, shaded; 0°–5°N). Both variables are computed from daily data. Only the easterly anomalies are shaded and the strong episodes before 1998 are denoted by the arrows. (b) Right panel: Hovmöller diagram of the monthly-filtered, interannual vorticity fluctuations (10^{-6} s^{-1}; 5°–20°N) with negative values shaded. Note the different temporal spans between the two panels.

with the statistics in Teng and Wang (2003), which were based on data collected during the period of 1958–2001. However, we did find that the ISO at 170°E was also significant in the springtime and from November to December 1997 (see Fig. 2 and Fig. 7a), when the mean vertical westerly shear dominated the western North Pacific. This implies that the interannual variability of the SO and ISO was not necessarily related to the vertical shear of the zonal-mean circulation. Indeed, the evolution of the SO and ISO were more consistent with that of vertical wind-shear anomalies than with that of the mean wind shear. Such a feature suggests that the anomalous vertical wind shear may contribute to the formation of the SO and ISO in the western North Pacific. Despite the fact that the remarkable change in the activity of the off-equatorial SO and ISO that was observed during the ENSO phase shift is still not fully understood. Further analysis on more ENSO events is needed to confirm the results obtained by this case study.

As delineated above, the warm episode of 1997 strengthened the easterly vertical-shear anomalies over the tropical Pacific (Fig. 8), and therefore led to the stronger than normal SO and ISO. The corresponding easterly phase of the SO and ISO that was observed over the western North Pacific, together with the counterpart of the LFO that was overturned from a westerly phase in October 1997 (Fig. 7b), triggered the upwelling Kelvin wave, which, in turn, dampened the warm event. The stronger the El Niño is, the more intense the atmospheric response, and thus, the stronger the SO and ISO that are produced. On the other hand, the westerly phase of the SO and ISO appeared, to a large extent, to be counteracted by the easterly phase of the LFO after October 1997. This did not benefit the occurrences of the westerly wind anomalies and thus, the opportunities for the excitations of the downwelling Kelvin waves were greatly reduced. This indicates that the regime shift of the 1997–98 El Niño was, at least partly, the result of the interactions between

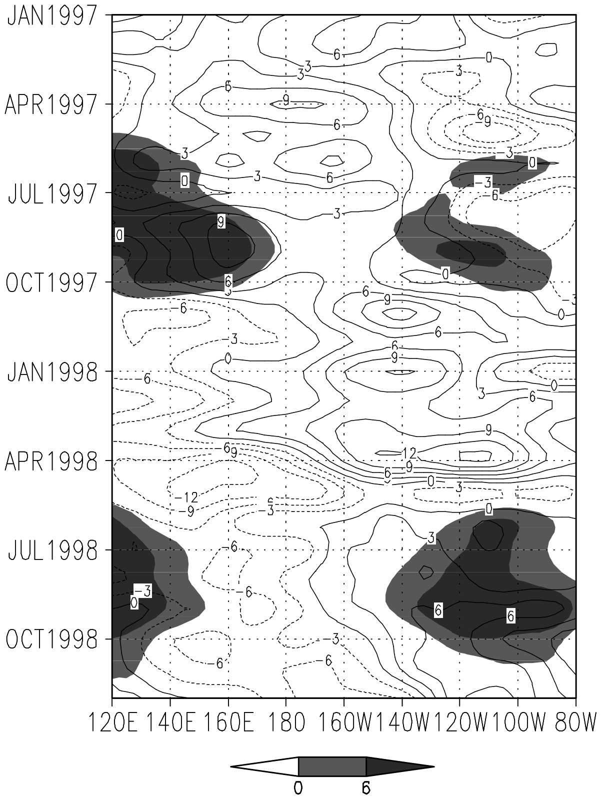

Fig. 8. Evolutions of the 5°–20°N mean zonal-wind vertical shear (U_{850}–U_{200}) (shaded) and its anomalies (contour). Only the mean easterly shear is shaded.

the multi-scale disturbances, e.g., SO, ISO and LFO, in the western North Pacific. Here, the phase shift of the LFO was due to a Gill-type response (Gill, 1980) to the peak phase of the warm SST anomaly over the equatorial central-eastern Pacific. Given that either high frequency or low frequency disturbances are closely associated with the forcing of El Niño, it is reasonable to deduce that the multi-scale atmospheric response in the western North Pacific to the warm SST anomaly served as an additional, self-provided, negative feedback for its reversal. Note that this deduction is derived from the case of the 1997–98 El Niño and that more case studies and numerical modeling are needed to confirm in the more generalized case.

6. Summary and discussion

In this study, we have shown that the off-equatorial vorticity over the tropical North Pacific exhibits significant fluctuations on the synoptic, intraseasonal and interannual timescales. These disturbances are distinguished from each other not only in the dominant periodicity, but also in their time evolution, spatial structure, and propagation. Evidence shows that the off-equatorial fluctuations are intimately involved in the establishment of the easterly episodes over the near-equatorial western Pacific during the phase transition of the 1997–98 El Niño event, implying their potential contributions to ENSO phase transition.

It is found that the off-equatorial SO and ISO fluctuations contributed to the occurrences of the near-equatorial easterly impulses in late 1997, which drove the upwelling Kelvin wave to terminate the El Niño, although the long-term tendency of the near-equatorial zonal flow was essentially modulated by the LFO component. Relative to the 2–7-yr period of ENSO, the SO and ISO in the lower-level winds identified in this study, served as a stochastic forcing on the ocean. The equatorial ocean responded most efficiently to the forcing in the form of eastward-traveling Kelvin waves, which may effectively fluctuate the thermocline of the central- and eastern-equatorial Pacific. Numerical modeling studies have indicated that the stochastic forcing, like MJO, not only introduces the irregularity of ENSO, but also acts to sustain the ENSO cycle (e.g., Roulston and Neelin, 2000; Zavala-Garay et al., 2003; Batstone and Hendon, 2005). In this sense, the activities of the ISO in the western North Pacific not only provided us a signal for predicting the decay and even the reversal of the El Niño, but somehow limited the predictability of the ENSO.

This case study suggests that the contribution of ISO in the western North Pacific to the ENSO phase transition heavily depends upon the phase of the LFO that is detected in Fig. 2. When the LFO-related near-equatorial zonal wind was in the easterly wind phase, the upwelling Kelvin wave induced by the SO- and ISO-related easterly, will be amplified, otherwise the role of SO and ISO would be counteracted by the LFO. Therefore, the LFO works like a slowly-varying background in which the SO and ISO are embedded. The SO and ISO work as a trigger to the phase-shift process of ENSO by inducing ISO Kelvin waves, thereby preconditioning the cooling of the SST in the equatorial eastern Pacific Ocean. The decay and reversal of the El Niño is the result of a multi-scale interaction in the coupled ocean-atmosphere system. In addition, the direct effect of the SO and ISO was to induce the Kelvin wave, but observational evidence shows that the onset of the Kelvin wave does not definitely induce the phase transition of ENSO. Therefore, the SO and ISO in the western North Pacific in the turnabout of 1997–98 El Niño acted as a kick-off factor in the phase transition through the excitation of an upwelling Kelvin wave.

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