Dynamical effect of the zonal wind anomalies over the tropical western Pacific on ENSO cycles

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Received May 8, 2001

Abstract The circulation and zonal wind anomalies in the lower troposphere over the equatorial western Pacific and their roles in the developing and decaying processes of the 1982—1983, 1986—1987, 1991—1992 and 1997—1998 El Niño events and the occurrence of La Niña events are analyzed by using the observed data in this paper. The results show that before the developing stage of these El Niño events, there were cyclonic circulation anomalies in the lower troposphere over the tropical western Pacific, and the anomalies brought the westerly anomalies over the Indonesia and the tropical western Pacific. However, when the El Niño events developed to their mature phase, there were anticyclonic circulation anomalies in the lower troposphere over the tropical western Pacific, and the anomalies made the easterly anomalies appear over the tropical western Pacific. A simple, dynamical model of tropical ocean is used to calculate the response of the equatorial oceanic waves to the observed anomalies of wind stress near the sea surface of the equatorial Pacific during the 1997/98 ENSO cycle, which was the strongest one in the 20th century. It is shown that the zonal wind stress anomalies have an important dynamical effect on the development and decay of this El Niño event and the occurrence of the following La Niña event.

Keywords: ENSO cycle, westerly anomalies, easterly anomalies, equatorial Kelvin wave, equatorial Rossby wave.

El Niño event can be considered as the most important phenomenon in the air-sea interaction over the tropical Pacific. The occurrence of El Niño event may cause severe climate anomalies, i.e. serious droughts, floods and low temperature and cooling disasters in many regions of the world. This can bring a large amount of losses of agricultural and industrial productions in many countries. The occurrence of El Niño event also brings severe climate disasters to our country. In the summers within the developing stage of El Niño event, droughts used to occur in North China, but in the summers within the decaying period of El Niño event, floods used to occur in the Yantze River valley. Therefore, meteorologists and oceanologists in China and many other countries pay much attention to the studies on the regularity and physical mechanism of ENSO phenomenon so that the occurrence of this phenomenon can be predicted in the future and the reliable information and physical basis can be provided to the prediction of climate disasters.

Bjerknes[1] first proposed a hypothesis that El Niño event is a result of air-sea interaction over the equatorial eastern Pacific. Up to now, there are a lot of studies on the formation mechanism of El Niño event and air-sea interaction. McCreary[2], McCreary and Anderson[3], Anderson and

McCreay[4] systematically investigated the physical mechanism of ENSO cycle. They put forward theoretically the role of the equatorial oceanic waves in ENSO cycle. Schopf and Suarez[5] interpreted the mechanism of ENSO cycle from the view point of unstable air-sea interaction and the propagation of the equatorial oceanic waves, and it was shown that the warm state of the West Pacific warm pool is a necessary condition for the occurrence of El Niño event. Only when the oceanic heat content (OHC) of the West Pacific warm pool is in an anomalous warm state, it is possible that an El Niño event occurs. However, in some years, the sea temperature of the West Pacific warm pool was in an anomalous high state and the OHC was anomalously large, but El Niño event did not occur in every other year during those years. This shows that the warm state of the West Pacific warm pool is only one of the necessary conditions for the occurrence of El Niño event, and the atmospheric state over the tropical western Pacific should be another necessary condition. Therefore, the atmospheric circulation anomalies over the tropical Pacific and wind stress anomalies near the sea surface of the tropical Pacific in the occurring process of El Niño event should be analyzed.

Philander[6]explained the dynamical effect of the relaxation of trade wind over the equatorial central and eastern Pacific on the warming of the equatorial eastern Pacific with numerical experiments. Tang and Weisberg[7] discussed the effect of the westerly anomalies of wind stress near the sea surface of the equatorial Pacific on the warming of the equatorial central and eastern Pacific during 1982—1983 with the numerical results simulated by a simple linear reduced-gravity model. However, these studies explained the effect of the westerly anomalies of wind stress near the equatorial Pacific on the warming of the equatorial eastern Pacific only with numerical experiments. Therefore, it is necessary to explain further the dynamical effect of the actual anomalies of zonal wind stress on ENSO cycle from the excitation of the actual wind stress anomalies on the equatorial oceanic waves theoretically. In this study, the evolution of the atmospheric circulations and wind fields in the lower troposphere over the tropical Pacific in these four El Niño events occurred in the period of 1980—1998 and their effect on these events, especially the dynamical effect of the zonal wind stress anomalies during 1997—1998 on the 1997/98 ENSO cycle, are analyzed and discussed by using the NCEP/NCAR reanalysis data and FSU wind fields near the sea surface of the tropical Pacific.

1 Zonal wind anomalies in lower troposphere over the tropical western Pacific and ENSO cycles

Fig. 1 is the interannual variations of the seasonal-mean SST anomaly averaging at NINO3 area in the equatorial eastern Pacific (fig.1(a)) and the zonal wind anomaly at 850hPa over the equatorial western Pacific (fig.1(b)) during 1980—1998. It may be clearly seen from fig. 1(a) that four strong El Niño events occurred in the equatorial central and eastern Pacific in 1982—1983, 1986—1987, 1991—1992 and 1997—1998 during 1980—1998, except for the weaker El Niño events occurring in 1993 and 1994. Among them the 1997—1998 El Niño event was the strongest in the 20th century. Moreover, It may be also seen that the obvious cold events, i.e. La Niña events, occurred in the equatorial central and eastern Pacific in 1984—1985, 1988—1989, 1995—1996 and the winter of 1998.

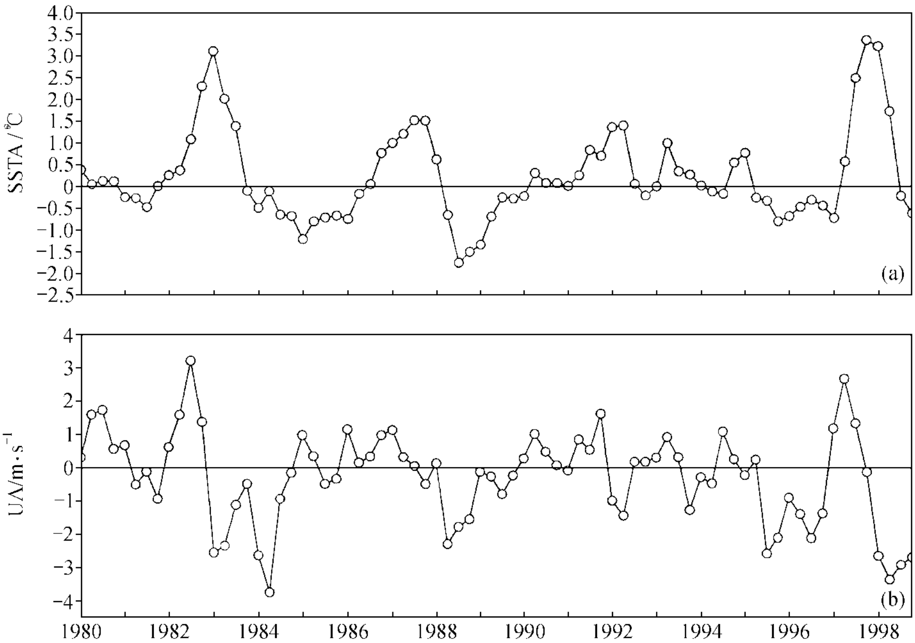

Fig. 1. Interannual variations of the seasonal-mean SST anomaly in NINO3 area (90—150°W, 5°N—5°S) in the equatorial eastern Pacific. (a) Unit: ℃ and the zonal wind anomaly at 850 hPa over the equatorical western Pacific (120—160°E, 5°N—5°S); (b) unit: m/s.

Fig. 1(b) shows that the interannual variations of zonal wind anomaly in the lower troposphere over the tropical western Pacific appeared as an oscillation. The stronger westerly anomalies appeared in the periods from the winter of 1981 to the autumn of 1982, from the winter of 1985 to the winter of 1986, from the spring to the autumn of 1991, and from the autumn of 1996 to the summer of 1997 before the developing stage of 1982—1983, 1986—1987, 1991—1992 and 1997—1998 El Niño events, respectively. Besides, the obvious westerly anomalies also appeared in the periods from the winter of 1992 to the spring of 1993 and in the summer of 1994, which was associated with the 1993 and 1994 weaker El Niño events. Moreover, it is also found from Fig.1(b) that before the occurrence of La Niña events, i.e. from the winter of 1982 to the summer of 1983, from the spring to the autumn of 1988, in the summer, autumn and winter of 1995 and from the winter of 1997 to the autumn of 1998, the easterly anomalies appeared over the tropical western Pacific. From these observed facts, it can be seen that there is close relationship between the ENSO cycles and the zonal wind anomalies in the lower troposphere over the equatorial western Pacific.

To compare fig. 1(a) with fig.1(b), it can be clearly seen that before the occurrence of these strong El Niño events, there were large westerly anomalies in the zonal wind anomalies at 850hPa over the equatorial western Pacific, while easterly anomalies appeared over the equatorial western Pacific before the occurrence of these four La Niña events. Huang and Zhang[8] analyzed the variations of zonal wind anomalies in the lower troposphere over the equatorial Pacific during the ENSO cycles occurring in the period of 1980—1994. Their study shows that there were strong westerly anomalies over the equatorial western and central Pacific in the developing stage of these El Niño events, and easterly anomalies appeared in the areas to the west of the westerly anomalies and extended eastward following the eastward propagation of the westerly anomalies. The results analyzed in this study are in agreement with the phenomenon found by Huang and Zhang[8].

2 Influence of atmospheric circulation anomalies in lower troposphere over the tropical western Pacific on ENSO cycles

The distributions of seasonal-mean wind anomaly fields of the atmospheric circulation anomalies at 850 hPa over the tropical western Pacific before the developing and decaying stages of these four El Niño events occurring in the period of 1980—1998 are analyzed by using the NCEP/NCAR reanalysis data. Fig. 2(a) and (b) is the distributions of the wind anomaly field at 850hPa over the tropical western Pacific in the summer of 1982 and the winter of 1997, respectively. It may be seen from these figures that before the occurrence of these El Niño events, there was an obvious cyclonic distribution of wind anomaly field in the lower troposphere over the tropical western Pacific and the obvious westerly anomalies over the Indonesia and the tropical western Pacific to the east of the Philippines. Similarly, the distributions of the wind anomaly field at 850hPa over the tropical western Pacific in the winter of 1985 and the spring of 1991 were analogous to those shown in fig. 2(a) and (b) (figures are omitted). The westerly anomalies were favourable for the formation of the warm Kelvin wave[9], and these anomalies made eastward transportation of the warm sea water in the West Pacific warm pool, thus, these El Niño events were caused. Fig. 2(c) and (d) is the distributions of the seasonal-mean wind anomaly field at 850hPa over the tropical western Pacific in the mature phase of these El Niño events, i.e. in the winter of 1982, and the autumn of 1997, respectively. It may be obviously seen that before the decay of these El Niño events, there was an obvious anticyclonic distribution of wind anomaly field. Thus, the obvious easterly wind anomalies appeared over the region from Pubua-New Guinea to Sumatra Island along the Indonesia. Similarly, the distribution of the wind anomaly field at 850 hPa over the tropical western Pacific in the autumn of 1987 and the spring of 1992 was analogous to those shown in fig.2(c) and (d). The easterly wind anomalies made the cold Kelvin wave form in the West Pacific warm pool, thus, these El Niño events were decayed and vanished and these La Niña events formed[9].

The above-metioned atmospheric circulation anomalies are associated with the convective activities over the tropical western Pacific. Ren and Huang's[10] investigation showed that when

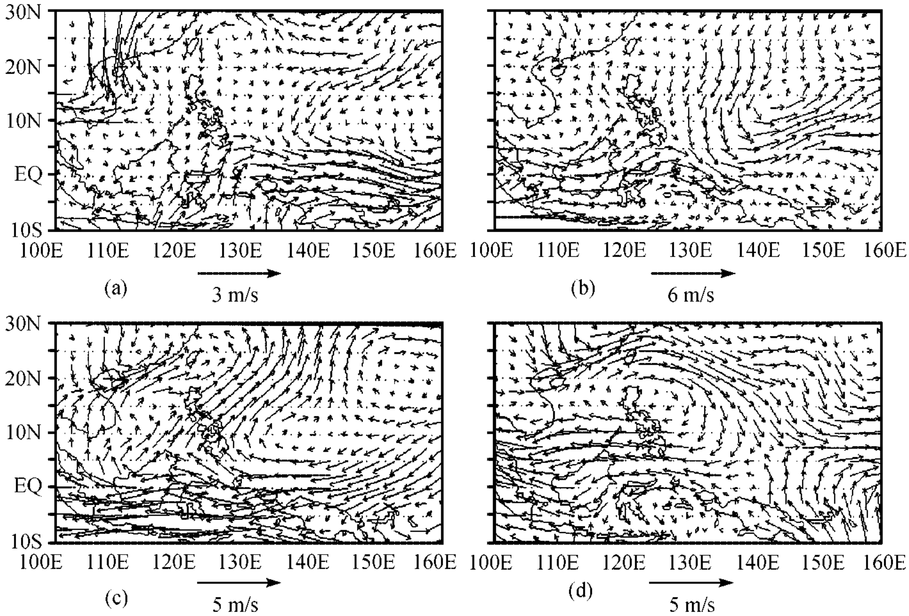

Fig.2. The distributions of wind anomaly field at 850hPa over the tropical western Pacific before the developing stages ((a) and (b)) and in the mature phase ((c) and (d)) of the El Niño events occurring in the period of 1980—1998, respectively. (a) In the spring of 1982; (b) in the winter of 1996; (c) in the winter of 1982; (d) in the autumn of 1997.

the West Pacific warm pool is in a warming (cooling) state, the convective activities are strong (weak) over the warm pool. The circulation anomalies may be inferred from the vorticity equation, i.e.

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{f+\zeta}{H}\right)=-fD,$$

where f is the Coriolis parameter, ζ the relative vorticity of atmospheric circulation, H the atmospheric representative-scale height and D the divergence of atmospheric circulation. When the convective activities are strong, the convergence of flow is intensified in the lower troposphere, i.e. $D<0$. Thus, $\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{f+\zeta}{H}\right)>0$. And if f is a constant, then $\frac{\mathrm{d}}{\mathrm{d}t}\zeta>0$. Therefore, a cyclonic circulation will be intensified over the tropical western Pacific. On the contrary, when the convective activities are weak over the tropical western Pacific, i.e. $D>0$, thus $\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{f+\zeta}{H}\right)<0$. And similarly, $\frac{\mathrm{d}}{\mathrm{d}t}\zeta<0$. Therefore, an anticyclonic circulation will be intensified over the tropical western Pacific.

From the above-mentioned analyses, it may be seen that there is a good relationship between the SST in the tropical Pacific, convections and circulation over the tropical Pacific. Therefore, the relationship between the atmospheric circulation anomalies and the equatorial oceanic waves will be analyzed in the following section.

3 A simple dynamical model of the tropical Pacific

In order to study the dynamical effect of the anomalies of zonal wind stress near the sea surface of the equatorial Pacific on the oceanic waves in the equatorial Pacific, according to Gill's study[11], under the equatorial β-plane approximation, nondimensionalized linear equations of shallow-water wave are given in the following, i.e.

$$\begin{cases} \frac{\partial u}{\partial t} - yv = -\frac{\partial h}{\partial x} + X, & (1) \\ yu = -\frac{\partial h}{\partial y} + Y, & (2) \\ \frac{\partial h}{\partial t} + \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0. & (3) \end{cases}$$

In the above-metioned equations, the definition of nondimensionalized variables is the same as Gill's definition[11], and X and Y are the nondimensionalized anomalies of zonal and meridional wind stresses, $X = \tau^x/[\rho H_0(c^3\beta)^{1/2}]$, $Y = \tau^y/[\rho H_0(c^3\beta)^{1/2}]$, respectively, $\rho = 1.026\times10^3 \text{kg/m}^3$, $c=(g' H_0)^{1/2}$, g' is the reduced gravity and is taken as 5.6×10^{-2} m/s^2. H_0 is the thickness of oceanic mixing layer and is taken as 150 m. β is the meridional gradient of the Coriolis parameter near the equator. τ^x and τ^y are the anomalies of zonal and meridional wind stresses near the sea surface of the tropical Pacific, respectively.

For the above-mentioned eqs. (1)—(3), the natural boundary conditions are taken in the meridional boundaries, and the boundary conditions in the eastern boundary $X=X_E$ and in the western boundary $x = x_w$ can be taken as follows:

$$u(y, x = x_E) = 0, \quad \int_{-\infty}^{\infty} u(y, x = x_W) dy = 0. \tag{4}$$

Introducing the new variables $q = h+u$ and $r = h-u$, and expanding the variables in eqs. (1)—(3) with the Weber function[11] $\Psi_m(y)$, i.e.

$$\begin{pmatrix} q(x,y,t) \\ r(x,y,t) \\ v(x,y,t) \end{pmatrix} = \sum_{m=0}^{\infty} \begin{pmatrix} q_m(x,t) \\ r_m(x,t) \\ v_m(x,t) \end{pmatrix} \Psi_m(y) \tag{5}$$

and considering only the forcing by zonal wind stress anomalies and taking only four orders in the expanded formula (5), then, eqs. (1)—(3) may become the following equations:

$$\frac{\partial q_0}{\partial t} + \frac{\partial q_0}{\partial x} = \int_{-\infty}^{\infty} X\psi_0 dy, \tag{6}$$

$$\frac{\partial q_2}{\partial t} - \frac{1}{3} + \frac{\partial q_2}{\partial x} = \frac{1}{3}\int_{-\infty}^{\infty} X\{\psi_2 - \sqrt{2}\psi_0\}\,\mathrm{d}\,y, \tag{7}$$

$$\frac{\partial q_4}{\partial t} - \frac{1}{7}\frac{\partial q_4}{\partial x} = \frac{1}{7}\int_{-\infty}^{\infty} X\{3\psi_4 - 2\sqrt{3}\psi_2\}\,\mathrm{d}\,y, \tag{8}$$

$$r_2 = 2\sqrt{\frac{1}{3}}q_4,$$

where eq. (6) represents the response of Kelvin wave, eqs. (7) and (8) indicate the response of Rossby waves of two-order and four-order, respectively. Thus, according to the observed anomalies of zonal wind stress near the sea surface of the tropical Pacific, the Kelvin wave and the Rossby waves responding to the anomalies of zonal wind stress anomalies can be solved from eqs. (6)—(8).

4 Dynamical effect of zonal wind stress anomalies on 1997—1998 ENSO cycle in the equatorial Pacific

In Sections 1 and 2, the relationship between the zonal wind stress anomalies and the developing and decaying of four El Niño events occurring in the tropical Pacific during 1980—1998 has been analyzed by using the observed data. In this section, the dynamical effect of the zonal wind stress anomalies near the sea surface of the tropical Pacific on the 1997—1998 ENSO cycle will be explained by using the Kelvin wave and the Rossby waves of two-order and four-order in the equatorial ocean, calculated from eqs.(6)—(8) and FSU zonal wind stress anomalies near the sea surface of the tropical Pacific.

The upper parts of fig. 3(a)—(c) indicate the Kelvin wave and the Rossby waves of two-order in the tropical Pacific responding to the observed anomalies of FSU zonal wind stress near the sea surface of the tropical Pacific in March, May and October, 1997, respectively, and the lower parts show the observed anomalies of zonal wind stress near the sea surface of the equatorial Pacific averaging between 5°N—5°S and the sea surface temperature anomalies (SSTA), respectively. Fig.3 (a) indicates that in March, 1997, since the strong anomalies of westerly wind stress appearred near the sea surface of the West Pacific warm pool, the warm Kelvin wave was excited in the equatorial western and central Pacific and the positive anomalies of SST were caused there. As shown in fig. 5(b), up to May, 1997, with the eastward propagation of the westerly anomalies of wind stress, the warm Kelvin wave propagated fastly eastward into the equatorial eastern Pacific, and it was reflected by the eastern boundary of the equatorial Pacific and became the warm Rossby waves, thus, the SST quickly increased in the equatorial eastern Pacific and the El Niño event bursted out in the equatorial eastern Pacific. Moreover, it is also found that the cold Rossby waves were excited in the equatorial western and central Pacific and these waves propagated westward. Up to July, 1997, the eastward-propagating warm Kelvin wave developed in the equatorial eastern Pacific, and the warm Rossby waves reflected by the eastern boundary of the equatorial Pacific continued to intensify (figure is omitted). This made the El Niño event intensify and the SST continued to increase in the equatorial eastern Pacific. Up to October, 1997, the warm Kelvin wave continued to develop in the equatorial eastern Pacific and the warm Rossby waves reflected by the eastern boundary also continued to develop in this region, as shown in fig.3(c). This made the SST develop to its top in the equatorial central and eastern Pacific, i.e. the El Niño event reached to its mature phase. Moreover, it may be also found from fig. 3(c) that the westward-propagating cold Rossby waves propagated into the West Pacific warm pool and developed there. This caused the cooling of the west Pacific warm pool and provided a pre-condition for the decaying of the El Niño event.

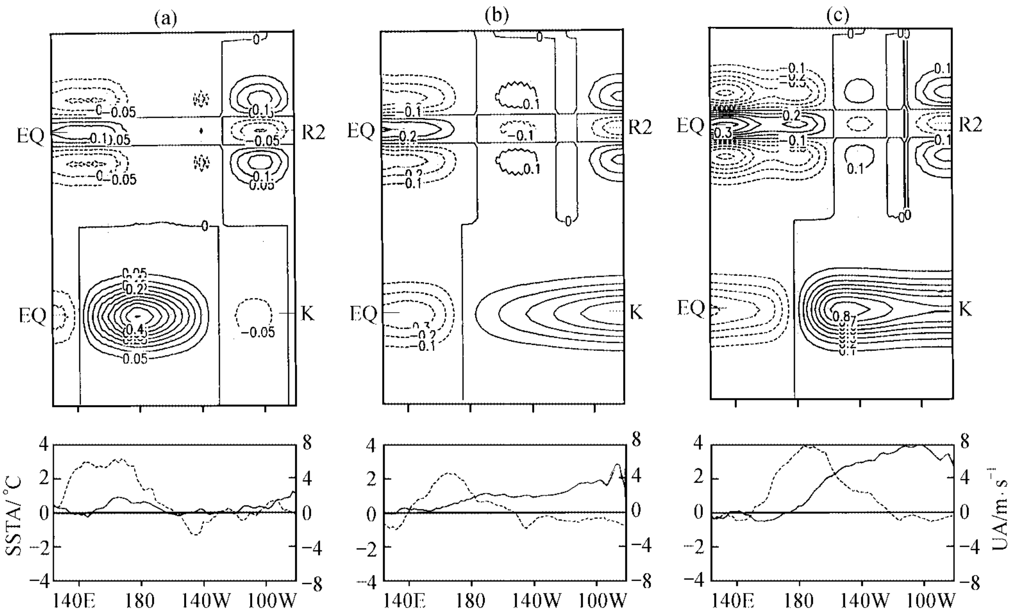

Fig. 3. The temporal spatial distributions of the equatorial oceanic Kelvin wave and Rossby waves responding to the anomalies of zonal wind stress near the sea surface of equatorial Pacific (upper part) and the observed SST anomalies in the equatorial Pacific (lower part, solid line) and observed anomalies of zonal wind stress near the sea surface (lower part, dashed line). (a) In March, 1997; (b) in May, 1997; (c) in October, 1997.

The upper parts of fig. 4(a) and (b) indicate the Kelvin wave and the Rossby waves of two-order in the tropical Pacific responding to the observed anomalies of zonal wind stress near the sea surface of the tropical Pacific in March and May 1998, respectively, and the lower parts show the observed anomalies of zonal wind stress near the sea surface of the equatorial Pacific averaging between 5N°—5°S and the SST anomalies, respectively. Fig.4 (a) denotes that in March, 1998, since the SST increased in the West Pacific warm pool and the larger anomalies of easterly wind stress appeared over this region, the cold Kelvin wave appeared in the equatorial western Pacific, and it propagated eastward. Moreover, it is also found that the warm Rossby waves appeared in the equatorial central and eastern Pacific. Up to May, 1998, due to the eastward propagation and development of the cold Kelvin wave, the SST decreased in the equatorial central Pacific, the El Niño event gradually decayed and vanished, as shown in fig.4(b). Moreover, it may be also found that the warm Rossby waves propagated into the West Pacific warm pool and made the SST gradually increase again in the warm pool. Up to August, 1998, the cold Kelvin wave propagated eastward into the equatorial central and eastern Pacific, and made the El Niño event vanish (figure is omitted). By this way, the El Niño event experienced the formation, developing, mature and decaying stages. Moreover, it is also found that the warm Rossby waves continued to develop again in the West Pacific warm pool, and made the SST increase again in the warm pool. This provided a pre-condition for next El Niño event.

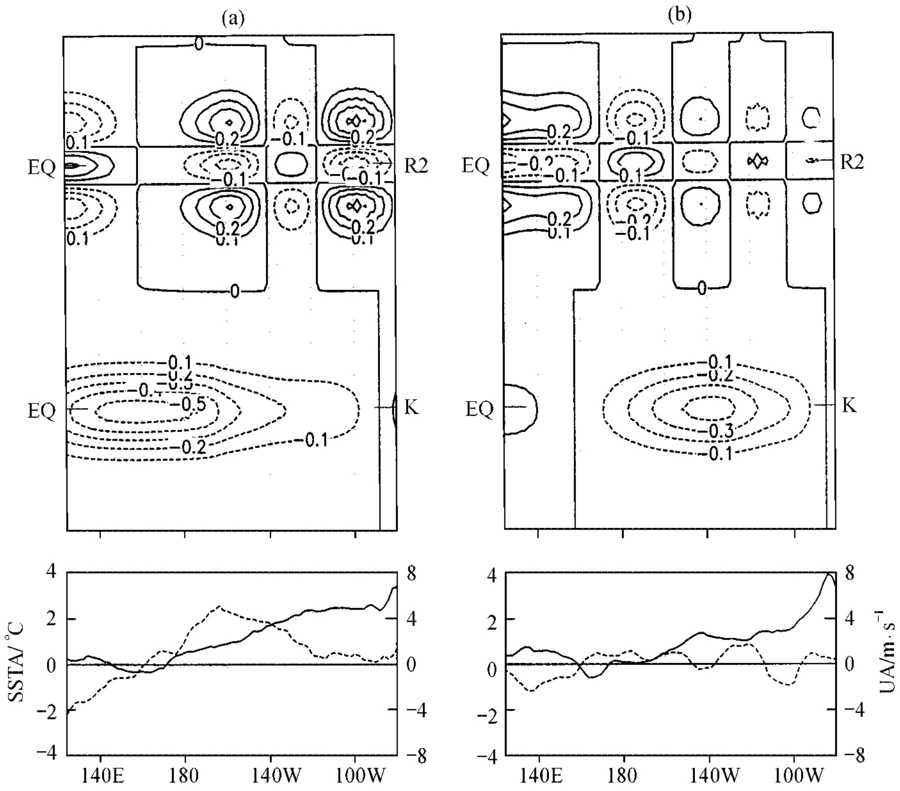

Fig.4. Same as in fig.3, except for in March (a) and May (b), 1998, respectively.

From the above-metioned temporal and spatial evolution of the Kelvin wave and the Rossby waves responding to forcing by the anomalies of zonal wind stress near the sea surface of the tropical Pacific, it may be seen that the westerly anomalies of wind stress near the sea surface of the tropical western and central Pacific play an important role in the occurrence and development of El Niño event in the equatorial Pacific, while the easterly anomalies of wind stress also produce significant dynamical effect on the decaying of El Niño event. Therefore, it may be said that the anomalies of zonal wind stress near the sea surface of the tropical western and central Pacific bring about an important dynamical effect on ENSO cycle in the tropical Pacific.

5 Conclusions

In this paper, the effect of the circulation and zonal wind anomalies in the lower troposphere over the western tropical Pacific on the development and decay of the El Niño events occurring in the period of 1980—1998 is analyzed by using the observed data of the SST in the tropical Pacific and the circulation fields and zonal wind anomalies at 850hPa. The results show that before the developing stage of these El Niño events there were obvious cyclonic circulation anomalies in the lower troposphere over the tropical western Pacific and the westerly wind anomalies over the equatorial western Pacific and Indonesia, while before the decaying stage of these El Niño events, i.e. in their mature phase, there were obvious anticyclonic circulation anomalies in the lower troposphere over the tropical Pacific and the easterly wind anomalies over the equatorial western Pacific and Indonesia.

The response of the equatorial Kelvin wave and Rossby waves to the observed anomalies of zonal wind stress near the sea surface of the tropical Pacific during the 1997—1998 ENSO cycle is discussed by using a simple dynamical model of the tropical ocean. The calculated results show that in the developing stage of the El Niño event, the westerly anomalies of wind stress near the sea surface of the tropical western Pacific could excite the eastward-propagating warm Kelvin wave and the westward-propagating cold Rossby waves, while in the decaying stage of the El Niño event, the easterly anomalies of wind stress near the sea surface of the tropical western Pacific could excite the eastward-propagating cold Kelvin wave and the westward-propagating warm Rossby wave. These waves had significant dynamical effect on the 1997—1998 ENSO cycle.

Acknowledgements This work was supported by the National Key Program for Developing Basic Research (Grant No. 1998040900).

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