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Mixed-layer water oscillations in tropical Pacific for ENSO cycle

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The main modes of interannal variabilities of thermocline and sea surface wind stress in the tropical Pacific and their interactions are investigated, which show the following results. (1) The thermocline anomalies in the tropical Pacific have a zonal dipole pattern with 160°W as its axis and a meridional seesaw pattern with 6—8°N as its transverse axis. The meridional oscillation has a phase lag of about 90° to the zonal oscillation, both oscillations get together to form the El Niño/La Niña cycle, which behaves as a mixed layer water oscillates anticlockwise within the tropical Pacific basin between equator and 12°N. (2) There are two main patterns of wind stress anomalies in the tropical Pacific, of which the first component caused by trade wind anomaly is characterized by the zonal wind stress anomalies and its corresponding divergences field in the equatorial Pacific, and the abnormal cross-equatorial flow wind stress and its corresponding divergence field, which has a sign opposite to that of the equatorial region, in the off-equator of the tropical North Pacific, and the second component represents the wind stress anomalies and corresponding divergences caused by the ITCZ anomaly. (3) The trade winds anomaly plays a decisive role in the strength and phase transition of the ENSO cycle, which results in the sea level tilting, provides an initial potential energy to the mixed layer water oscillation, and causes the opposite thermocline displacement between the west side and east side of the equator and also between the equator and 12°N of the North Pacific basin, therefore determines the amplitude and route for ENSO cycle. The ITCZ anomaly has some effects on the phase transition. (4) The thermal anomaly of the tropical western Pacific causes the wind stress anomaly and extends eastward along the equator accompanied with the mixed layer water oscillation in the equatorial Pacific, which causes the trade winds anomaly and produces the anomalous wind stress and the corresponding divergence in favor to conduce the oscillation, which in turn intensifies the oscillation. The coupled system of ocean-atmosphere interactions and the inertia gravity of the mixed layer water oscillation provide together a phase-switching mechanism and interannual memory for the ENSO cycle. In conclusion, the ENSO cycle essentially is an inertial oscillation of the mixed layer water induced by both the trade winds anomaly and the coupled ocean-atmosphere interaction in the tropical Pacific basin between the equator and 12°N. When the force produced by the coupled ocean-atmosphere interaction is larger than or equal to the resistance caused by the mixed layer water oscillation, the oscillation will be stronger or maintain as it is, while when the force is less than the resistance, the oscillation will be weaker, even break.

tropical Pacific, thermocline and sea surface wind stress anomaly, ENSO cycle, mixed layer water oscillation

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1 Introduction

The ENSO event, which occurs under the influence of strong air-sea interaction in the Tropical Pacific, is a strong signal for interannual climate variability, having a great impact on global climate. Over the past fifty years, a large amount of researches have been made on the occurrence of ENSO event; many theories have been proposed concerning its formation and cycle. Although these theories are capable of explaining some features of the ENSO onset and evolution, the fundamental cause for its onset is still unclear, and its prediction is still far from satisfaction. The ENSO cycle has experienced remarkable changes since the 1980s; its predominant period increased from the 2 to 3 years before the 1970s to the 4 to 5 years during the 1980s[1,2]; its amplitude increased markedly as well[3]. Prior to the 1970s, the El Niño events were mainly of the east type, i.e., its remarkable sea surface temperature rise appeared along the coastal areas of South America first and then extends westward. After the 1980s, however, they were of the middle type[4], i.e., its remarkable temperature rises appeared first in the central equatorial Pacific and then moved eastward. The observations since the 1980s have indicated that there might be relatively long time intervals leading to the interruption of the ENSO cycle[5], as seen in 1980—1981, 1985, 1989—1990, briefly in mid-1996 and during 2000 through 2001. Sometimes an ENSO event seemed to occur but died halfway, like the weak warm event in 1980 which came to a premature end. On the other hand, sometimes an event is about to terminate but soon appears again, like the weak El Niño events appeared in 1993 and 1994/1995. These events cannot by fully explained and let alone predicted by existing research achievements, implying that still have not completely understand the formation mechanisms of the ENSO cycle.

During the past half century, a great number of studies have been carried out to better understand the ENSO mechanism. For the first time Bjerknes[6] explained these events in terms of the viewpoint of air-sea interaction, suggesting that the development of El Niño is due to a positive feed back process between the eastern equatorial Pacific SST and the Walker circulation over it. Wytrki[7] proposed a trade wind relaxation theory to explain the formation of El Niño events, suggesting that ENSO events be closely related to the zonal pressure gradients formed by the accumulation of warm water in the western Pacific induced by strong trade winds. However, both theories cannot predict the occurrence of subsequent events. Observations since the 1980s have indicated that ENSO acts more like a kind of cycle (than a single event), hence leads to the birth of a series of new theories to explain this phenomenon. On the basis of the studies by McCreary, Cane and Zebiak, and Battisi and Hirst[8−10], Suarez and Schopf[11] put forward the "delayed oscillator" theory, where equatorial wave propagations and the reflection of the western boundary were emphasized. A number of ENSO cycle processes have been explained and predicted by this theory. Some other theories similar to the delayed oscillator theory were proposed, such as Weisberg and Wang's[12] "the western Pacific oscillator" and Picaut et al.'s[13] "the advective-reflective oscillator". Combining the view points of Bjerknes, Wytrki, and Cane and Zebiak，Jin[14] proposed "the recharge and discharge oscillator" for the upper-layer warm water in the equatorial Pacific. This model is capable of explaining the process of ENSO cycle, which is basically in agreement with the delayed oscillator and more universal as it does not rely upon the propagation of equatorial waves. However, there are also some theoretical studies, which are not in agreement with the traditional ENSO theory. Chao and Philander[15] studied the ENSO cycle by means of a coupled ocean-atmosphere model, pointing out that there is no clear evidence of the existence of equatorial waves in the interannual variability related to ENSO cycle. Masumota and Yamagata[16] made a detailed analysis of the structure of oscillatory solutions, pointing out that there are merely eastward propagation disturbances in the solutions with no clear evidence of the existence of Rossby waves. Zhang and Chao[17] proposed the possible role in the ENSO cycle played by self-excitation produced in a coupled nonlinear tropical ocean-atmosphere system, suggesting that an ENSO cycle could be maintained without propagation of the equatorial wave system within the ocean and its reflection at the eastern boundary. The study by Huang, Zhang and Yang et al.[18−21], on the other hand, paid more attention to the important role of the zonal wind stress anomaly over the Pacific and its eastward propagation in the ENSO cycle, pointing out a close relationship between the meridional wind stress variation over the eastern tropical Pacific and the occurrence of El Niño events. However, there are two problems as for concerning the ENSO cycle theories mentioned above. One is that the ENSO cycle is considered only in the equatorial Pacific and its process is analyzed only on the basis of the ocean-atmosphere interaction in the equatorial Pacific, while the role of tropical and subtropical large-scale ocean circulations was ignored. The other is that these theories are established on the basis of interannual time scales, therefore the effects of interdecadal variability on the ENSO cycle were ignored.

The previous observations and studies have shown that there is a significant interdecadal variability in the Pacific sea temperatures. Zhang et al.[22] discovered that the Pacific SST possessed ENSO-like interdecadal vari ability with periods of about 11 years. White et al.[23] discovered sub-ENSO interdecadal variability with 9—13 and 18—23 years in period in the upper-layer temperatures of the global ocean. Analyzing 150 years' Pacific SST data, Zhao et al.[24] found that in addition to the 2—7 years period ENSO also has the interdecadal variability with a period of 11—17 years, with an average of 14 years, which had an important effect on the ENSO cycle. More recently, Chen et al.[25] shows that the interdecadal time scale variability has an important contribution to the thermal and dynamical variability of the tropical even the entire Pacific. For this reason, in order to obtain the better results, which are in better agreement with the observations, it is necessary to remove the interdecadal or longer variations from the raw time data series in studying the ENSO cycle, which is characterized mainly by interannual variability.

The observed facts and studies show that the ENSO cycle as an ocean-atmosphere phenomenon not only appears in the equatorial Pacific but is also related to the coupled ocean-atmosphere system in the entire tropical Pacific. For the first time Zebiak[26] discovered the fact that there were net meridional transports of heat content across the equator in the tropical Pacific during the ENSO cycle. Utilizing the upper ocean temperature data and ocean meteorological data, Zhang and Levitus[27] studied the interannual variability of the coupled climate system in the tropical Pacific. They pointed out that during the onset of El Niño, the positive heat content anomalies over the thermocline in the western tropical Pacific propagated eastward along the equator; at the same time there were the negative heat content anomalies in the eastern equatorial Pacific moving northward along the coast of America, then, crossing the tropical North Pacific along the latitude of 15°N, and after reaching the western Pacific they propagate southward and enter the equatorial waveguide region. This implies that the ENSO cycle may be a slowly evolving coupled ocean-atmosphere phenomenon in the tropical Pacific, not a phenomenon resulting from the propagation of independent oceanic Rossby and Kelvin waves. Afterwards, utilizing the coupled ocean-atmosphere model (CGCM), Yu and Mechoso[28] simulated successfully the coupling process during the ENSO cycle, and confirmed the observed results mentioned above. In recent years, Chao et al.[29,30] and Li[31] analyzed the propagation of the subsurface layer ocean temperature anomalies in the tropical Pacific and discovered that the anomalous ocean temperature signals forming ENSO events propagated eastward along the equator at the thermocline depth from the West Pacific to the East Pacific and then propagated away from the equator, at the same time there existed a anomalous ocean temperature signal with opposite signs propagating westward along the latitudes of 10°S and 10°N respectively and then turn towards the equator to form two complete cycles. The above results reveal a new evolving process for El Niño/La Niña events, providing a factual basis for further understanding the mechanism of the ENSO cycle.

From the above analysis it can be concluded that it is necessary to conduct deeper research into ENSO cycle mechanisms, to establish a new model for the ENSO cycle which will be able to accord better with practical observations. A great number of El Niño studies in the past were mainly based on SST variations. But in essence, SST variations are merely a phenomenon displayed at the sea surface for the existence of ENSO events; it is the depth variation of the thermocline that is the most important factor signifying the onset and ending of El Niño/La Niña events, and is the optimum index in studying ENSO phenomenon. However, not much research was made about the analysis of observed thermocline data due to the limitations of marine observed data at one time in the past. With the improved understanding of the role of the thermacline and the rapid accumulation of observed data, considerable progress has been made on the study of the thermocline in the Pacific. We adopt sea temperature anomalies at the climatic thermocline surface as basic data in this paper, which are closer to real situations, are used to characterize thermo cline depth anomalies. Then, by analyzing their interannual variability in time and space, we study the evolution of thermocline depth anomaly and the interaction between it and the sea surface wind stress anomaly field to explore new ENSO cycle mechanisms and to improve ENSO prediction.

2 Data and its processing method

The Oceanic and atmospheric data utilized in this study is mainly the Simple Ocean Data Assimilation (SODA1.4.2) reanalysis data set provided by University of Maryland, USA, sea surface wind stresses calculated from the reanalysis wind data ERA-40 produced by the European Center for Medium-Range Weather Forecasts[32,33]1), and the ocean subsurface temperature (XBT) observation data collected by Joint Environmental Data Analysis Center (JEDAC), Scripps institute of Oceanography, USA. In this study the data we used are the ocean temperature field data covering 528 months (from Jan. 1958 to Dec. 2001 inclusive), ranging from 30°S to 30°N, divided into 20 layers in the vertical direction within 600 m. In this study we mainly make use of the SODA data set with the XBT data for comparison if necessary. The wind field data ERA-40 is based on reanalysis daily surface wind field data of the ECMRWF (Jan. 1958 to Dec. 2001), whose errors are even smaller than those of COADS and NCEP wind fields.

There are many methods to estimate thermocline depth anomaly. Usually the depth of the 20° or 14℃ isotherm is utilized to represent the thermocline depth. But the 20℃ isotherm is not suitable for the East Pacific cold water region because it can reach the surface in cold seasons; on the other hand, isotherm 14℃ seems to be too deep in the Western Pacific warm pool region. In addition, some researchers used the heat content in the upper layer and sea level height as the thermocline depth anomaly. Based on the observed fact that the maximum sea temperature anomalies generally appear near the thermocline, Chao et al.[30] used such a curved surface of depth at which the subsurface temperature anomalies reach their maximums to replace the thermocline surface. Recently Qian et al.[34] also pointed out that the thermocline depth anomaly could be characterized by the vertical subsurface temperature anomaly because it can memorize the change in ocean-atmosphere interaction signals and store energy in the upper layer of the ocean, thus it is a better factor in controlling the climate variability than the SSTA. On the basis of the above results and Chao et al.'s method, and by use of the 44 years' data of sea temperature anomalies within the upper 600 m in the Pacific Ocean, we analyzed the depth distribution of the curved surface for the maximum variance of sea temperature anomalies (Figure 1), assuming that it can basically represent the curved sur-

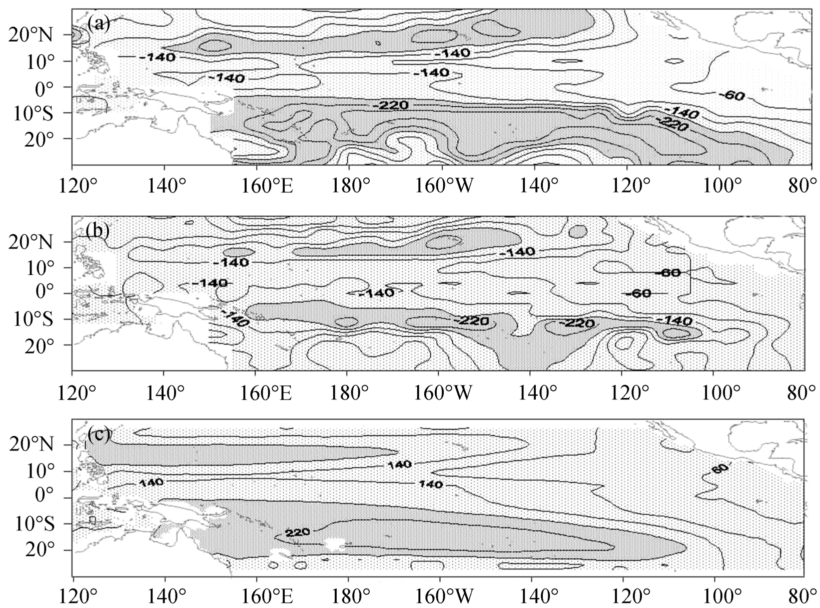

Figure 1 Distributions of the thermocline depth (m) in the Pacific obtained by calculation with different data sets and methods (contour interval is 40 m), a, SODA data set; b, XBT data set; c, depth of the 20℃ isotherm.

1) Conton J A, Giese B S. SODA: A reanalysis of Ocean Climate. J Geophys Res, submitted, 2006

face of the climatic thermocline depth. Figure 1 shows the climatic thermocline depth surfaces calculated by using the SODA and XBT data sets respectively and the depth distribution of the 20℃ isotherm in the tropical Pacific. Generally speaking, except for the fact that the values obtained from the SODA data set tend to be larger, the distribution trends of the two are basically in agreement with each other in the tropical regions north of 20°S. Within this region, the SODA data set covering a larger area is more reliable. In the tropical Pacific, apart from the area in the northwest, the results from the SODA data are very close to the depth distribution of the 20℃ isotherm. In view of the above, this study is based on the SODA data, using the temperature anomaly over the thermocline surface in the data set as an index to characterize the thermocline anomaly. The distribution of the climatic thermocline surface in the tropical Pacific can be seen in Figure 1(a). It is shaped like a trapezoidal mesa in the tropical Pacific (20°S－20°N), whose depths from the west to the east change from the deeper to the shallower and the width from the narrower to the wider. The depth of the warm pool can reach 140 m in the West Pacific, but it is smaller than 60 m in the East Pacific in the tropical regions of the North and south sides of the mesa outside the equatorial region, and there is a deep trough on each side whose maximum depth is greater than 200 m. The trough to the north is in the direction northeast by east and southwest by west, with its depth center in the central-eastern Pacific. The trough to the south is in the direction southeast by east and northwest by west, with its depth center in the central Pacific. Obviously the deep troughs in the tropical regions around the equator are closely related to the powerful subtropical circulations in the north and south Pacific. The seawater sinks under the action of anticyclonic eddies, leading to a deepening of the thermocline.

An analysis of the observed data indicates that the vertical gradients of ocean temperatures above the thermocline surface are relatively small. Therefore we name the upper layer ocean as the mixed layer water where the temperature above the thermocline is relatively well-distributed. This water includes the water of the traditional mixed layer defined in oceanography and the water body from its bottom to the middle of the thermocline. A positive temperature anomaly at the thermocline surface implies that the thermocline depth becomes deeper and the mixed layer water becomes thicker, and vice versa. In other words, the variation of the thermocline depth characterizes the variation of the mixed layer water thickness. For simplicity, the mixed layer water will be termed the mixed layer hereafter. In order to understand the formation mechanism and evolution of the thermocline during the ENSO cycle, in this paper we first determine the climatic thermocline surface in the tropical Pacific by using the SODA data and then work out the sea temperature anomaly at the thermocline surface as a thermocline depth anomaly index. Since the ENSO cycle has the interannual variability of the 2 to 7 year period, we conduct the 1 to 8 year band pass filtering of the thermocline anomaly index to separate interannual variability, followed by the EOF analysis. The long-term trends are eliminated in the filtering. A similar procedure is performed for the sea surface wind stress data.

3 The main modes of the interannual variability of the mixed layer water thickness anomaly in the tropical Pacific

Figure 2 shows the first (a) and second (b) modes and their time series (c) obtained by the EOF decomposition (un-standardized) of the interannual variability of the thermocline depth anomaly (TCA) in the tropical Pacific after the 1－8 year band pass filtering. They account for 25.2% and 14.8% of the total variance, respectively, and the overall contribution of the two reaches as high as 40.0%. As analyzed in Sec. 2, they characterize the main feature and time variability of the mixed layer water thickness anomaly. The main distribution features of the first mode in space are: in the tropical area between 20°S and 20°N, there is a dipole type distribution of TCA in the direction from east to west, with the longitude of 160°W or so as its axis. One of the extreme TCA is located near the warm pool region and 150°E north of the equator in the western tropical Pacific, the other is located between 90° and 120°W south of the equator in the eastern tropical Pacific with absolute values slightly greater. The main feature of spatial distribution of the second mode is that there is a seesaw shaped TCA distribution in the tropical Pacific, with 6－8°N as its zonal axis on an average, to the north and south of which there exist TCA regions with large values of opposite signs, located in the middle and eastern North Pacific around 10－15°N (12°N on an average) and the middle equatorial Pacific, respectively. Spectral analysis (Figure 2(d)) shows that both the first and second modes

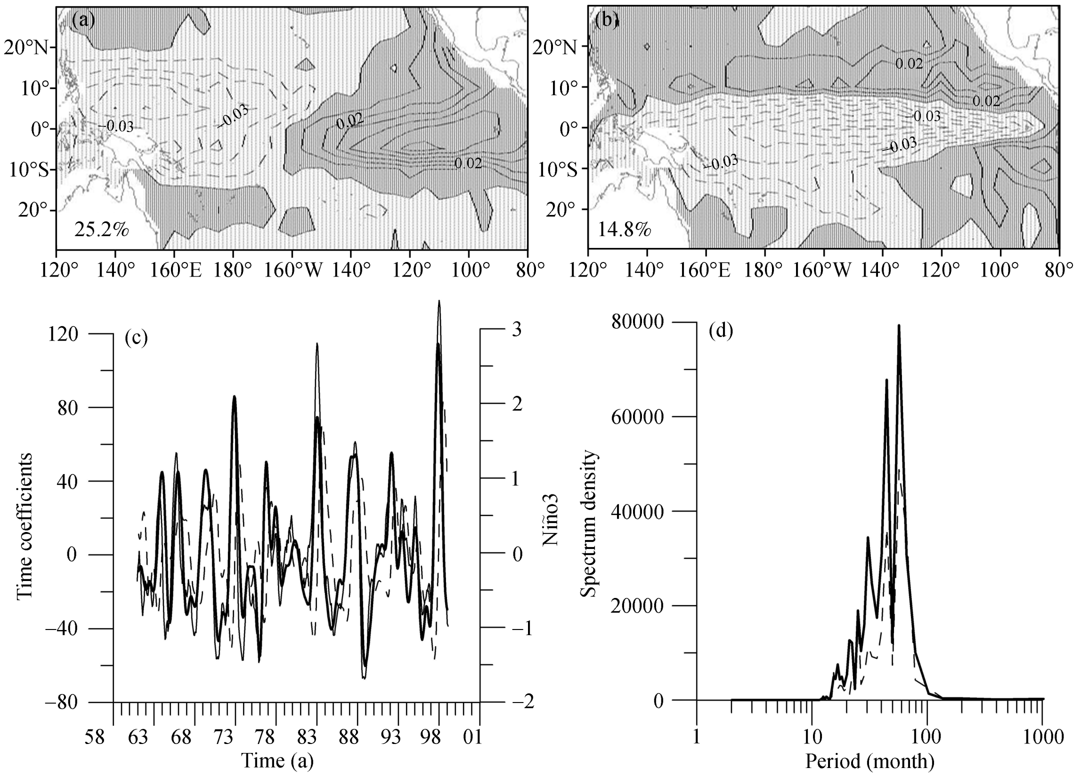

Figure 2 Time-space distributions of the first (a) and second (b) modes of the interannual variability of TCA in the tropical Pacific (solid lines show positive values, dashed lines show negative values, contour interval is 0.01℃), corresponding time series (c) and spectral analysis results (d) (thick solid line for the first mode; dashed line for the second mode, thin solid line shows Niño3).

possess two significant periods: 56 and 44 months. There exists an optimum simultaneous correlation between the time series of the first mode and Niño 3 (the SST index in the region 5°S—5°N, 90°—150°W) with r = 0.90; and an optimum delayed correlation between the time series of the second mode and Niño 3 with r = 0.78 and the optimum delayed time being 8—9 months. Except for the two weak El Niño events in 1993 and 1994—1995, the above mentioned modes manifest themselves in all the ENSO events that occurred in the past 40 years distinctly, such as the El Niño events in 1963/1964, 1965/1966, 1968/1969, 1972/1973, 1976/1977, 1982/1983, 1986/1987, 1991/1992, 1997/1998, and the La Niña events in 1964/1965, 1967/1968, 1970/1971, 1973/1974, 1975/1976, 1984/1985, 1988/1989 and 1995/1996. The contributions of the third or more TCA modes account for all less than 3.6% to the total variance, and these are no reliable correlation between their time series and Niño3. From the viewpoint of TCA this implies that, there are two kinds of modes for ENSO events, the first mode mainly shows itself as a TCA dipole distribution with 160°W as its meridional axis in the direction from east to west in the tropical Pacific, signifying an unstable state of the tropical mixed layer water inclined in the west to east direction, and the second mode mainly appears as a TCA seesaw distribution with the 6—8°N area as its zonal axis, signifying an unstable state of the tropical mixed layer water inclined in the north to south direction.

Similar analysis was also made on the heat content and sea level height anomaly in the tropical Pacific, the results we obtained were quite similar to those for TCA in terms of eigenvector fields in space and time series varying synchronously (figures omitted), implying that when the thermocline deepens, the heat content will increase, the sea level height will rise and the mixed layer water will thicken, and *vice versa*.

4 The oscillation features of the mixed layer water in the tropical Pacific during El Niño/La Niña cycles

Using the first and second modes, we combined them to obtain the reconstructed fields of interannual variability of the thermocline depth anomaly in the tropical Pacific during El Niño/La Niña cycles to characterize the oscillation process of the mixed layer water in the tropical Pacific. Figure 3 shows the propagation process of the interannual variability of the TCA in the tropical Pacific in 1981—1984, which was a complete El Niño/La Niña cycle process that occurred after an approximately 4 year long calm period from 1977 to 1980. In the Figure 3 the positive TCAs indicate that the mixed layer water is thick, while the negative TCAs indicate that it is thin. It can be seen clearly that in January 1981 a TCA distribution started to appear in the tropical Pacific which was deep in the west and shallow in the east. By September 1981 there were the remarkable positive TCAs in the middle and western equatorial Pacific and remarkable negative TCAs in the eastern tropical Pacific. By January 1982, the positive TCA center had propagated eastward to the middle of the equatorial Pacific, while the negative TCA center had been split into two with the maximums located in the America's coastal sea areas on both sides of the equator, respectively. In March 1982, the TCA extremum in the equatorial area was greater than +2.0℃, and near 12°N in the eastern equatorial Pacific there appeared remarkable negative TCAs, with its center being situated along North America's coastal seas, where the TCA extremum was less than −1.0℃. By May 1982, the center of positive anomalies had propagated eastward along the equator to the central eastern Pacific, the TCA extremum reaching +2.5℃. At this time the SSTA increased sharply and an El Niño event onset. At the same time, the negative anomaly center situated in the north of the eastern tropical Pacific propagated westward along 12°N with the TCA extremum being less than −1.0℃. Another negative anomaly center located in the south of equator gradually weakened and eventually disappeared. By now the TCA distribution had the features of the second EOF eigenvector field. Afterwards, the positive anomaly signals in the middle and eastern equatorial Pacific continued to propagate eastward, intensified and extended both

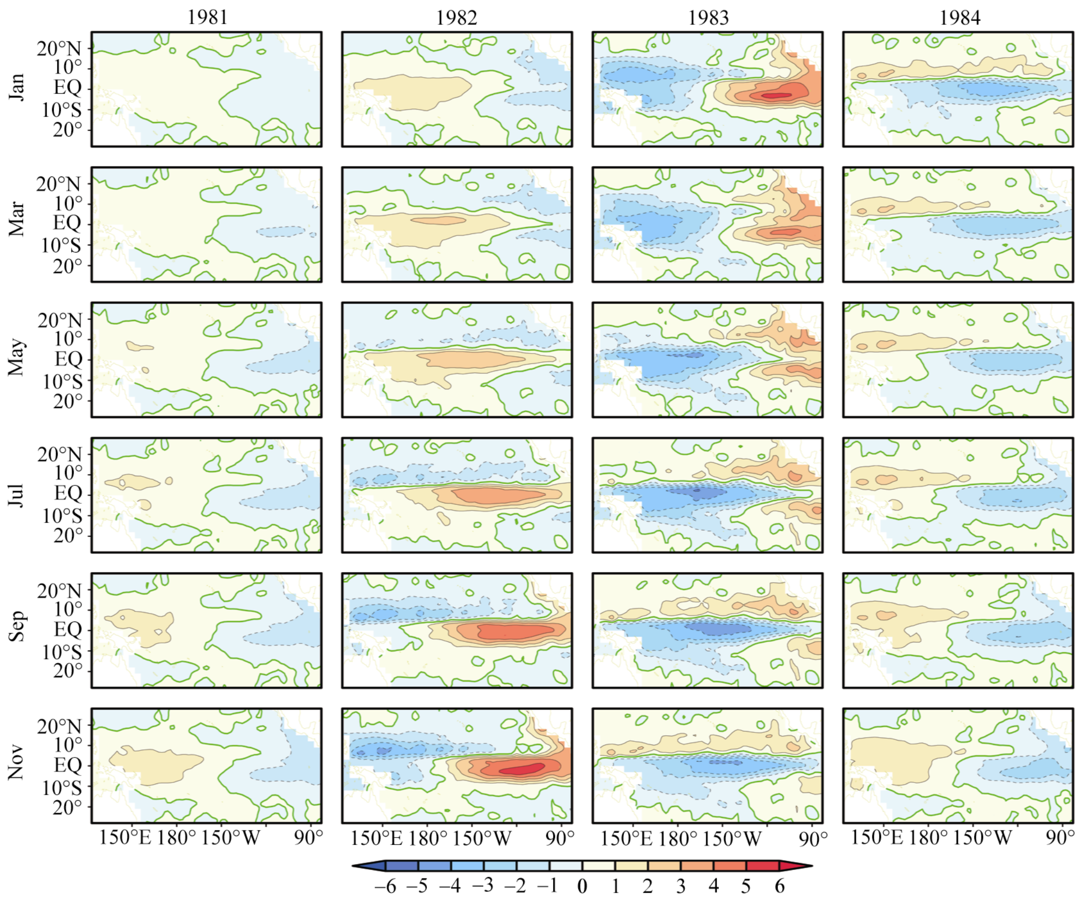

Figure 3 An evolving process of the TCA in the tropical Pacific during 1981 to 1984 (solid lines show positive values, dashed line show negative values, contour interval given by the color bar is 1.0℃).

northward and southward on reaching the east boundary of the eastern equatorial Pacific. On the other hand, the negative anomaly located in the north part of the eastern tropical Pacific continued to move westward along 12°N, intensified and extended southward on arriving at the boundary of the western equatorial Pacific. The two reached their peaks with their extreme TCA of +5.0℃ and −3.5℃ respectively in early 1983 when the El Niño event entered its mature stage. At the same time, the TCA distribution had changed into the features being of the first EOF eigenvector field. Afterwards, the negative TCA signals in the western equatorial Pacific started propagating along the equator and at the same time the positive TCA center in the eastern tropical Pacific extended both northward and southward, with the center in north side moving westward along 12°N, while the center in south side weakening and vanishing. By September 1984, the negative TCA center had arrived at the boundary of the eastern equatorial Pacific and extended both northward and southward, the extreme TCA at the center was less than −2.5℃ and at the same time the positive TCA center also moved westward along 12°N, intensified and extended southward with its extreme TCA of greater than +2.0℃ on arriving at the boundary of the western tropical Pacific. Thus a weak La Niña event occurred in October, and an ENSO cycle completed. At the end of 1984, an evolving process occurred, which started the same process as occurred at the end of 1981, and so did the El Niño event in 1986/1987 (figures omitted). It was also noticed that during the formation of El Niño/La Niña events, there appeared TCA centers moving away from the equator in the south of the eastern equatorial Pacific, but they did not develop but weakened and disappeared instead.

From the above analysis it can be concluded that the first mode of the TCA determines the TCA amplitude in the El Niño/La Niña events, while the second mode characterizes the phase change of the cycle process. The combined effects from the two lead to the El Niño/La Niña cycle. Based on a cross spectral analysis of the two TCA modes of El Niño events, it can be shown that the second mode lags behind the first mode by approximately 1/4 period. Therefore we can describe the mixed layer water oscillation model in the tropical ocean during the ENSO cycle by combining the two modes as given in Figure 4. The time interval between two successive figures in Figure 4 is 1/8 period, where solid lines indicate that the TCA is higher, which means that the thermocline is deeper and the mixed layer is thicker; dashed lines indicate exactly the opposite case. From Figure 4 we see that the El Niño/La Niña cycle is in reality the result of repeated anticlockwise 3-D oscillations of the mixed layer water in the tropical Pacific basin between the equator and 12°N. The oscillations appear in the form of propagations along the above described TCA routes. Thus it can be seen that an El Niño event will occur when the mixed layer water in the tropical Pacific is thin in the west and thick in the east, and a La Niña event will occur when it is thick in the west and thin in the east. An El Niño event will be developing when the mixed layer water is thick along the equator but thin along 12°N in the tropical North Pacific basin. On the other hand, a La Niña event will be developing when the mixed layer water is thin along the equator and thick along 12°N in the tropical North Pacific basin.

5 The main modes of wind stress anomaly in the tropical Pacific and their relations to ENSO

First, the sea surface wind stresses calculated from the reanalysis wind data ERA-40 were filtered by the band pass filter with the 1—8-year window and its trend was removed in filtering to get the interannual variability of wind stress anomalies (WSA) in the tropical Pacific, then it was decomposed by the EOF analysis. Figure 5 shows the first three modes of the WSA and their time series in the tropical Pacific, where vectors are the WSA, contours the abnormal divergence field, and the divergence area is showing by light shading, the convergence area by dark shading. The first mode (Figure 5(a)) of the WSA accounts for 20.3% of the total variance, there are stronger zonal WSA in the central and eastern equatorial Pacific, and obvious meridional WSA in the both sides of equator and in the eastern and western boundaries of the tropical Pacific, and obvious WSA crossing equator from the South Hemisphere in the off-equatorial tropical North Pacific and in the latitudes of equator to 10°N. Corresponding divergence field, the stronger poleward (equatorward) cross-equatorial flow causes stronger divergence (convergence) in the equatorial Pacific, and stronger (weaker) cross-equatorial flow causes stronger convergence (divergence) in the region of 5—15°N. Therefore they form opposite phase of anomaly divergence fields in the equatorial Pacific and in the 5—15°N region of the tropical North Pacific. It is noted that they

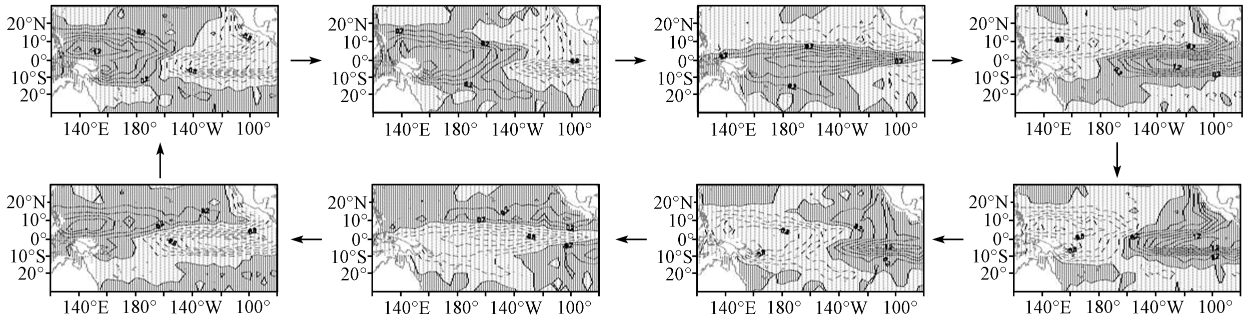

Figure 4 An oscillation models of the mixed layer water in the tropical Pacific during the ENSO cycle (contour interval is 0.2℃).

occur simultaneously along the equator and in the 5—15°N region of the tropical North Pacific, and the stronger the trade wind, the stronger the cross-equatorial flow, therefore the stronger the divergence along the equatorial Pacific and the stronger convergence in the region of the 5—15°N tropical North Pacific; the weaker the trade wind or the westerly anomaly the weaker the cross-equatorial flow, therefore the weaker the divergence or the stronger the convergence along the equatorial Pacific and the weaker the convergence or the stronger the divergence in the region of the 5—15°N tropical North Pacific. Evidently, the first mode actually corresponds to the change of trade wind in the tropical Pacific. Its time series has obvious interannual variability responding to the variation of trade winds system in the equatorial Pacific. Niño 3 has a best correlation to the first mode with lags of zero and +1—2 months, and its maximum correlation coefficient reaches 0.86, showing the close relationship between the anomaly trade wind of tropical Pacific and the El Niño events. It has corresponded to all of the ENSO events one by one in the past more than 40 years. During the 1963, 1965, 1968/1969, 1972/1973, 1976, 1982/1983, 1986/1987, 1991/1992, 1993, 1994/1995 and 1997/1998 El Niño events, the westerly anomalies and the equatorward flow anomalies prevailed and caused obvious convergence anomaly in the equatorial Pacific, and equatorward N flow anomalies and obvious divergence anomaly in the region of the 5—15°N tropical North Pacific. During the 1964, 1967/1968, 1970/1971, 1973/1974, 1975/1976, 1984/1985, 1988/1989, 1995/1996 and 1998 La Niña events, the easterly anomalies and the poleward flow anomalies prevailed and caused obvious divergence anomaly in the equatorial Pacific, and obvious convergence anomaly in the region of the 5—15°N tropical North Pacific. The spectrum analysis results show that, it has obvious ENSO periods of 44 and 56 months and quasi bi-annual 30 months period of the tropical atmospheric system. The second mode (Figure 5(b)) accounts for 15.0% of the total variance. Its main features characterized by the band-like WSA divergence field, which is formed by confluence of the cross-equatorial SW wind stress from the South Pacific and the NE trade of the North Pacific in the north side of equator along 5°N of the eastern and central Pacific and around 10—15°N of the western tropical Pacific. These main features are located in the position of the climatic inter-tropical convergence zone (ITCZ), representing the interannual variability of ITCZ. There is a good correlation between the second mode of leading 4—5 months and Niño3 with $r = 0.68$, which shows that the earlier ITCZ has some influence on the El Niño onset. The spectrum analysis results show that, it has significant periods of 30, 44 and 56 months. That means that the quasi bi-annual period of the tropical atmospheric system is dominant and the ENSO periods of the second mode are next. The third mode (Figure 5(c)) account for 10.0% of total variance, whose main features are characterized by the significant WSA of the tropical Pacific with the equator as a symmetric axis, of which the WSA centers in both sides of equator with same phase and the axis trends northward from the south side of equator in the eastern tropical Pacific to the north side of equator in the western tropical Pacific. There are no significant correlation between Niño3 and the earlier WSA showed by third mode, but Niño3 has some correlation to the third mode with a lag of 6 months and $r = -0.38$. It suggests that, the third mode of the WSA have no significant relations to Niño 3, but the lagged WSA may be the effects of El Niño on the surface wind. Spectrum analysis shows periods of 36 and 28 months. The modes 4 or more account for less than 8.9% of the total variance,

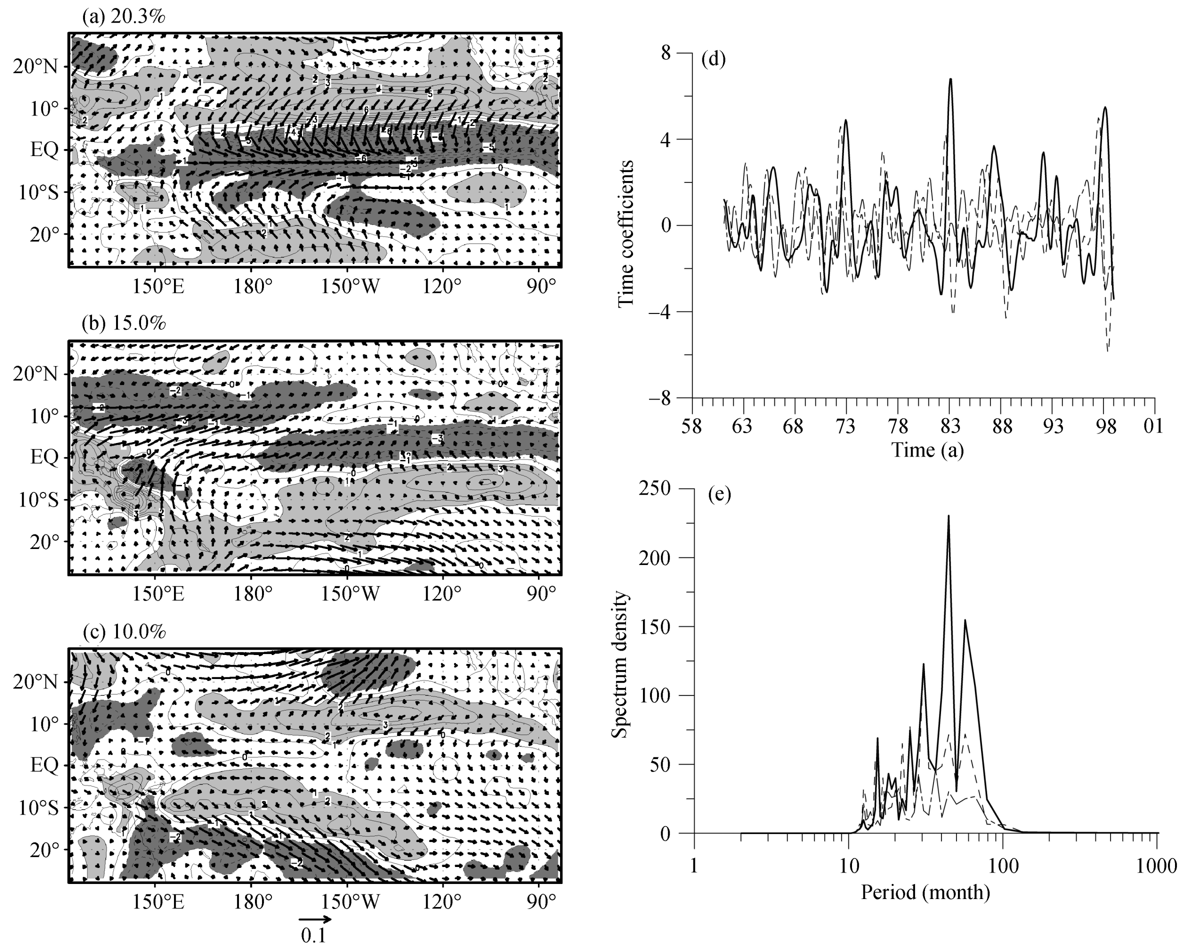

Figure 5 The first three EOF modes (a, b, c) of WSA in the tropical Pacific (the vectors are WSA (10^{-1} N/m^2), the contours show the WSA divergence field and its interval given by the shading bar is 1×10^{-9} N/m^3, divergence in light shading, convergence in dark shading) and their time series and spectrum analysis results (d, e, solid line, dashed line and dot-dashed line for the first, second and third modes, respectively.)

which are no significant correlations to Niño 3. Wyrtki[7] proposed a “build-up” of warm water in the western equatorial Pacific by stronger than normal trade winds for a year or more, and indicated that, the trade winds play an important role in El Niño evolution. This proposal is similar to the close correlation between the first mode and Niño3 shown in present paper. Many years ago, Philander[35] has discovered that the anomaly shift southward of ITCZ can be an indication for the El Niño onset. Zhang et al.[36] indicated further that the meridional WSA related to the ENSO events may occur ahead of 6 months or more, which characterized by the anomaly convergence in the central and eastern equatorial Pacific with northerly WSA in the north side of equator and southerly WSA in the south side of equator. These results are similar to the correlations between the second mode and El Niño shown in present paper. In view of the above points, the trade wind anomaly is the most important and the ITCZ anomaly formed by the meridional trade wind anomaly from both Hemispheres also has some important contribution to the ENSO cycle. According to the cross spectrum analysis of first two modes, the second mode lags behind the first mode by a phase of about 90°, which is a lag similar to TCA.

6 Physical processes of the mixed layer water oscillation in the tropical Pacific

The correlation between the main modes of WSA and the main modes of TCA shows that there are close correlations between the first two modes of WSA and the TCA (Figure 6). It is focused here only on the influence of WSA on the TCA in the same stage (including lags of −1, zero and +1 months) and the later stage. It can be seen from Figure 6 that the first mode of WSA has the most important effects on the first two modes of TCA, it has the best correlation to the first mode of TCA with lags of zero and −1 months and r = 0.86, and to the second mode of TCA with the 7 months lag and r = 0.80. The former relation corresponds to the interaction between the trade winds system of the tropical Pacific and ENSO cycle, which is a decisive factor for the strength of ENSO events, and the later relation shows the influence of anomaly trade winds on the phase transition of ENSO cycle. The second mode of WSA in the tropical Pacific has a good correlation to the second mode of TCA with lags of zero and −1 months and the first mode of TCA with 5 month lag, the correlation coefficients are −0.67 and 0.71, respectively. According to the eigenvector of the second mode shown in Figure 5, the WSA divergence in the western and central tropical Pacific of the north side of the equator will lead to the westward movement of the TCA in the tropical North Pacific along 12°N, the WSA divergence in the eastern equatorial Pacific will result in the eastward movement of the TCA in the equatorial Pacific along the equator. That implies that the abnormal ITCZ has some influence on the phase transition of ENSO cycle, and also can be a leading indicator for the ENSO event onset.

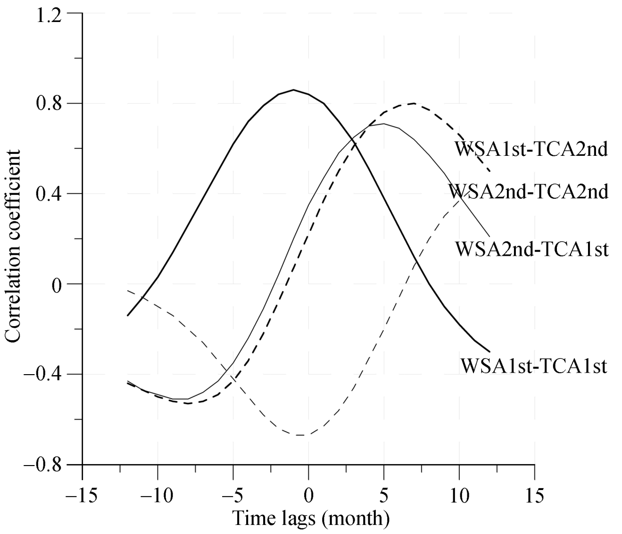

Figure 6 The lag correlations between the first two modes of wind stress anomalies (WSA) and the first two modes of thermocline depth anomalies (TCA) in the tropical Pacific.

Figure 7 shows the evolution of divergence fields composed by the first two modes of WSA in the tropical Pacific from 1981 to 1984, representing the combined effects of the trade wind anomaly and ITCZ on the WSA divergence. In Figure 7 Contours show the WSA divergence field, solid line for divergence, >10 in light shading, dashed line for convergence, <−10 in dark shading. Compared to the evolution of TCA in the tropical Pacific during the same period (Figure 3), the interaction processes between WSA and TCA are revealed during ENSO cycle. From the beginning of 1981, the trade WSA of the tropical Pacific intensified gradually first in the central and eastern Pacific, then the significant anomaly divergence occurred in the equatorial Pacific and the significant anomaly convergence occurred in the off equator of the tropical North Pacific, showing the first mode (trade wind anomaly pattern) distribution. Meantime, the warmer water built up in the western boundary of the tropical Pacific and the colder water spread upward in the eastern boundary of the tropical Pacific, showing a TCA dipole pattern with being deeper in the west part and shallower in the east part of the tropical Pacific in September 1981. Later, the WSA in equatorial Pacific intensified further, and the WSA convergence in the 5—15°N region of the tropical North Pacific also intensified simultaneously and reached their strongest peak in March 1983, then weaken gradually. At that time, for the TCA evolution, the deeper TCA center moved eastward along the equator, the shallower TCA center in the eastern Pacific divided into two parts, of which the one in the north side of equator moved westward along 12°N, and the other in the south side of equator weakens and disappeared finally, showing a TCA seesaw pattern with being deeper in the south part and shallower in the north part of the tropical Pacific, then the El Niño event setup in May 1982. In July 1982, the trade WSA weakened and transited to the westerly WSA in the equatorial Pacific, the abnormal poleward S flow weakened and transited to the abnormal equatorward N flow in the 5—15°N region of the central and eastern tropical North Pacific, showing the second mode (the ITCZ anomaly pattern) of the WSA in the tropical Pacific. At that time, the trade WSA has the lowest contribution to the WSA divergence fields. Corresponding to the TCA evolution, it becomes shallower in the western Pacific and deeper in the eastern and central Pacific. Later, a stronger band-like wind stress convergence occurred in the eastern and central equatorial Pacific and a stronger band-like wind stress divergence occurred in the central and eastern tropical North Pacific, and a TCA dipole pattern with being shallower in the west part and deeper in the east part of the tropical Pacific, which shows the

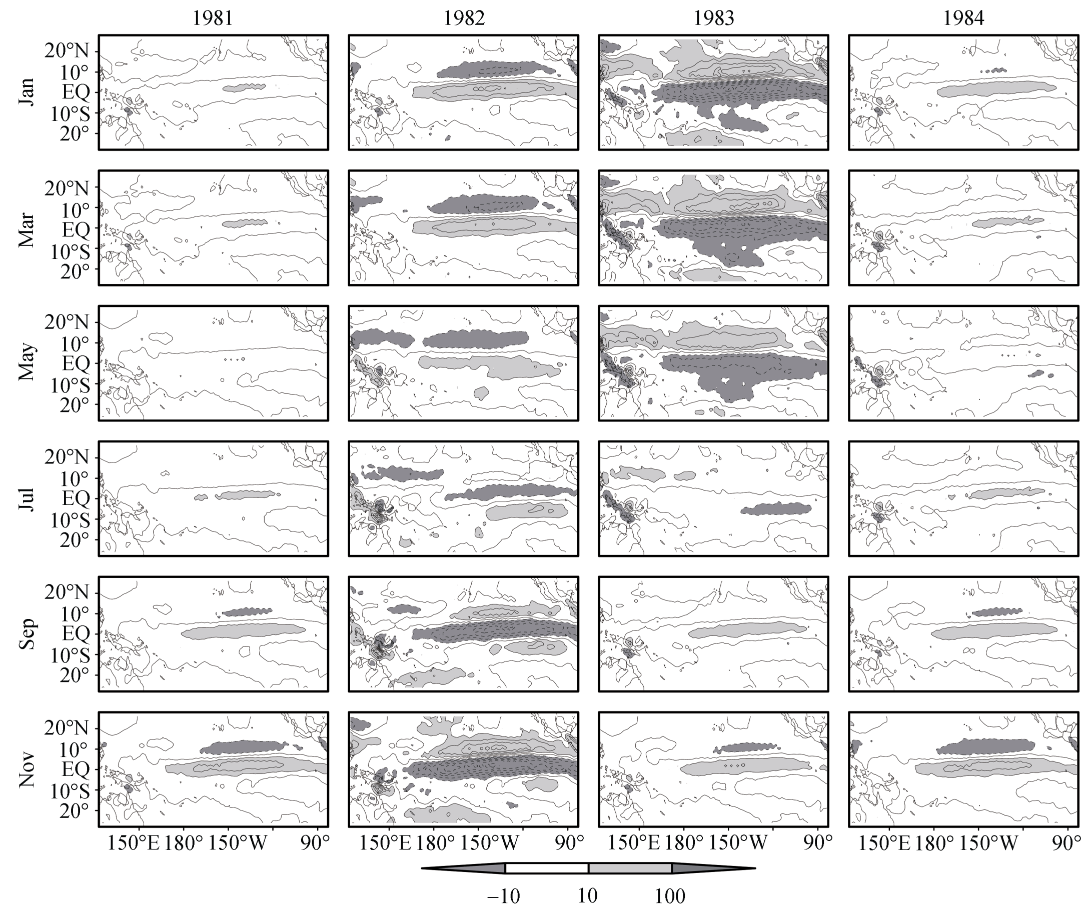

Figure 7 The evolution of the wind stress anomaly divergence in the tropical Pacific composited by the first two modes from 1981 to 1984 (the contour interval given by the shanding bar is 10×10^{-9} N/m^3, solid line for divergence, >10 in light shading, dashed ling for convergence, <10 in dark shading).

El Niño reaching its mature stage in the earlier of 1983. Owing to the WSA divergence moving westward and extending from 5—15°N to 20°N of the tropical North Pacific, it has no relations to the ENSO events, representing the effects of the ITCZ anomaly on the western tropical Pacific. In the following stage, the evolutions of the WSA divergence field and TCA show a similar process to that in September 1981 to January 1983 but with the opposite signs, and then a weak La Niña event occurred in October 1984 and reached its mature stage in December 1984.

The above analysis shows that the trade winds intensifying in the tropical Pacific is a prerequisite from El Niño onset, and the ENSO cycle is always accompanied by the change of the trade winds and ITCZ. That indicates that, the intensifying of both trade winds and ITCZ and therefrom the significant WSA divergence in the equatorial Pacific and the significant WSA convergence in the 5—15°N region of the tropical North Pacific happen with a La Niña event onset simultaneously; while the trade winds and ITCZ weakening and therefrom the significant WSA convergence in the equatorial Pacific and significant WSA divergence in the 5—15°N region of the tropical North Pacific happen with an El Niño event onset simultaneously; when the trade winds or westerly anomaly and therefrom the WSA divergence in the equator Pacific and the opposite phase of the WSA divergence in the 5—15°N region of the tropical North Pacific reach their peaks, ENSO events will reach their mature stage.

Theoretical studies so far have indicated that the ocean thermocline anomaly is mainly caused by the redistribution of ocean internal structure, in which resulted by the ocean dynamic anomaly processes driven by the surface WSA. The warm water build-up hypothesis proposed by Wyrtki[7] considers that the stronger trade winds induce the warm water build-up in the western tropical Pacific and form the pressure gradient force from the west to the east in the equatorial Pacific, as soon as the trade winds weaken or westerly becomes abnormal, the warm water in the western tropical Pacific will move eastward and upwelling in the eastern tropical Pacific will weaken, resulting in an El Niño event. Zhang and Levitus[27] pointed out that the coupled interaction between SST, surface winds and the ocean thermocline would give rise to coherent propagation of subsurface anomaly patterns, and the continual movement of subsurface thermal anomaly on and off the equator provides a phase-switching mechanism and an interannual memory for the tropical climate system. Yu and Mechoso[28] have simulated successfully the physical processes of air-sea interaction during ENSO cycle. They displays that the thermal anomaly evolution along the equator is out of phase with that along 10°N of the tropical North Pacific, the evolution of upper-ocean (shallower than 300 m) heat content in the tropical Pacific is characterized by a zonal oscillation between the western and eastern tropical Pacific and a meridional oscillation between the equator and 10°N. They further indicated that the heat content anomaly in the western and eastern boundary region mainly caused by the vertical displacement of the thermocline, the heat content anomaly in the equatorial central Pacific mainly caused by the meridional, zonal and vertical advection processes, and the heat content anomaly along 10°N of the tropical North Pacific basin mainly contributed by vertical advection process. From the above results and the facts revealed in present paper, we can clearly understand the oceanographic essentials as well as their coupled tropical ocean-atmosphere processes during the ENSO cycle. In the pre-onset stage of El Niño, if the trade winds continued to intensify slowly, the warm water builds up in the western boundary of tropical Pacific owing to the topographic obstruction and forms downwelling and horizontal poleward advection, inducing the thermocline to deepen and to widen, and the off-coast westward flow causes cold water to go up in the eastern boundary of the tropical Pacific owing the topographic effect and forms upwelling and equatorward advection, inducing the thermocline to shoal and to widen. Because the initial condition of the mixed layer water is rather homogeneous and the ocean horizontal and vertical advections are smaller, there are no significant anomalies occurred in the equator and off-equator of the tropical Pacific. When the trade wind anomaly and the eastward pressure gradients caused by mixed layer water with thicker in the west and thinner in the east reached their balance, the thermocline in the tropical Pacific will display deeper in the west and shallower in the east, being the La Niña state and getting ready for the subsequent El Niño event onset. An El Niño event onset begins when the trade winds weakened or westerly wind anomaly intensified, which made the eastward pressure gradient force stronger than the trade wind stress anomaly and caused them to lose their balance. Owing to the gravity of the mixed layer water, the thermocline goes up in the west and down in the east, then the warmer water will move eastward and therefore induces an El Niño event. Meantime, the warmer water located in the tropical western Pacific causes heating anomaly and stronger convection takes place over there, then the westerly wind anomaly occurred on its west side will move eastward along the equator with the eastward moving warmer water, therefore the weak trade wind or westerly winds anomalies will occur in the western and central Pacific, which will cause the trade wind stress anomaly of the equatorial Pacific to weaken gradually and to transit to the westerly wind stress finally, and will induce abnormal convergence, and the divergence field will transit from the divergence to the convergence. Based on the WSA mode of the tropical Pacific, it simultaneously causes the poleward S wind stress in off-equator of the tropical North Pacific to weaken and to transit to the N wind stress finally, and to induce abnormal divergence; the divergence field will transit from the convergence to divergence. According to the Ekman Pumping theory, the abnormal divergence will induce the thermocline to deepen along the equator and to shoal along the 12°N of the North Pacific. At the same time, the ocean dynamic anomaly processes of the mixed layer water imply that downwelling and the horizontal poleward flow in the western boundary of the tropical Pacific will weaken gradually and transit to upwelling and the horizontal equatorward flow, then the thermocline will go up finally, and the warmer water will be replaced by the colder water; and in the equatorial Pacific, the westward and poleward flows and vertical positive advection will weaken gradually and finally transit to the eastward and equatorward flows and downwelling, then the deepening of thermocline continually propagates eastward along the equator; in the eastern boundary of the tropical Pacific, the upwelling and the horizontal equatorward flow will weaken gradually and finally transit to the downwelling and the horizontal poleward flow, and the thermocline will go down, then the colder water will be replaced by the warmer water. In the tropical North Pacific along 12°N, the ploeward S flow weakens gradually and transits to the equatorward N flow finally, and the horizontal convergence and vertical negative advection weaken gradually and transit to the horizontal divergence and upwelling advection, inducing the thermocline to shoal. Owing to the initial condition of thermocline with being shallower in the east and deeper in the west and the general trend of thermocline variation with being up in the west and down in the east, the shoaling thermocline continually propagates westward along 12°N of the north Pacific basin. At that time, the thermocline deepens along the equator and shoals along 12°N of North Pacific basin, showing seesaw pattern with being deeper in the south and shallower in the north. Afterwards, the deepening thermocline propagates along the equator to the eastern boundary of the tropical Pacific and extends poleward in both sides of the equator owing to the topography obstruction, meantime, the shoaling thermocline propagates westward around 12°N to the western boundary of the tropical Pacific and extends equatorward owing to the topography obstruction, completing the meridional propagation of the mixed layer water. So far, the thermocline anomaly in the tropical Pacific shows a dipole pattern with being deep in the east and shallow in the west and forms an El Niño event. Owing to the inertia gravity of the mixed layer water, the colder water reaching to the western tropical Pacific moves eastward along the equator continually, and the thermocline anomaly shows that it goes down in the west and up in the east. Meantime, the colder water located in the tropical western Pacific causes the cooling anomaly at the sea surface and the convection decending over there, the easterly wind anomaly occurred on its west side moves eastward along the equator with the eastward moving colder water, therefore the weak westerly wind anomaly or strong trade winds occur in the western and central Pacific, which induces the westerly wind stress anomaly of the equatorial Pacific to weaken gradually and to transit to the easterly wind stress finally, then causes anomaly divergence, and the convergence field will transit from the convergence to the divergence. Meantime, the N WSA at around 12°N in the tropical North Pacific will weaken and transit to the S WSA, inducing abnormal convergence field from divergence to convergence. Due to the Ekman pumping, the thermocline will shoal along the equator and deepen at around 12°N in the tropical North Pacific. After passing the corresponding abnormal dynamical processes in the ocean, a La Niña event forms finally and a phase transition ends at last, and a full ENSO cycle completes. It is noted that during the ENSO cycle, owing to the interaction between the ocean thermal anomaly and the WSA in the western tropical Pacific, an El Niño (La Niña) event is always accompanied by the westerly (easterly) wind anomaly, the wind anomaly extends eastward along the equator with the mixed layer water oscillation, which induces the trade WSA and causes the wind stress convergence (divergence) along the equator and WSA divergence (convergence) in the 5—15°N region of the tropical North Pacific, which therefore produces a divergence field conducing to simultaneous thermocline variations in the equator and off the equator, which, in turn further intensifies the mixed layer water oscillation. It is the processes of the coupled ocean-atmosphere system in the tropical Pacific that induce the corresponding abnormal ocean dynamic process and ensure the proceeding of ENSO cycle. It is understood from the simple dynamical analysis that the major forces for maintaining the mixed layer water oscillation are the inertia gravity, the force produced by the coupled ocean-atmosphere system and the resistances of water viscosity and topography obstruction. When the force produced by the coupled ocean-atmosphere system is larger than or equal to the resistances of water viscosity and topography obstruction, the inertia gravity of mixed layer water will increase or maintain, and when the force produced by the coupled ocean-atmosphere system is smaller than the resistances of water viscosity and topography obstruction, the inertia gravity of mixed layer water will decrease owing to the resistance, and the mixed layer water oscillation will be weak and even pause, which possibly causes ENSO cycle to break finally. Evidently, the processes of the coupled ocean-atmosphere system in the tropical Pacific have an important contribution to maintaining the mixed layer water oscillation, together with the inertia gravity of oscillation, which provide a phase-switching mechanism and an interannual memory for ENSO cycle. Figure 8 shows a concept model including the above physical processes and representing the coupled ocean-atmosphere model for the ENSO event formation and cycle and its break. Based on the above analyses, it is concluded that, the ENSO cycle is a mixed layer water oscillation in the tropical Pacific

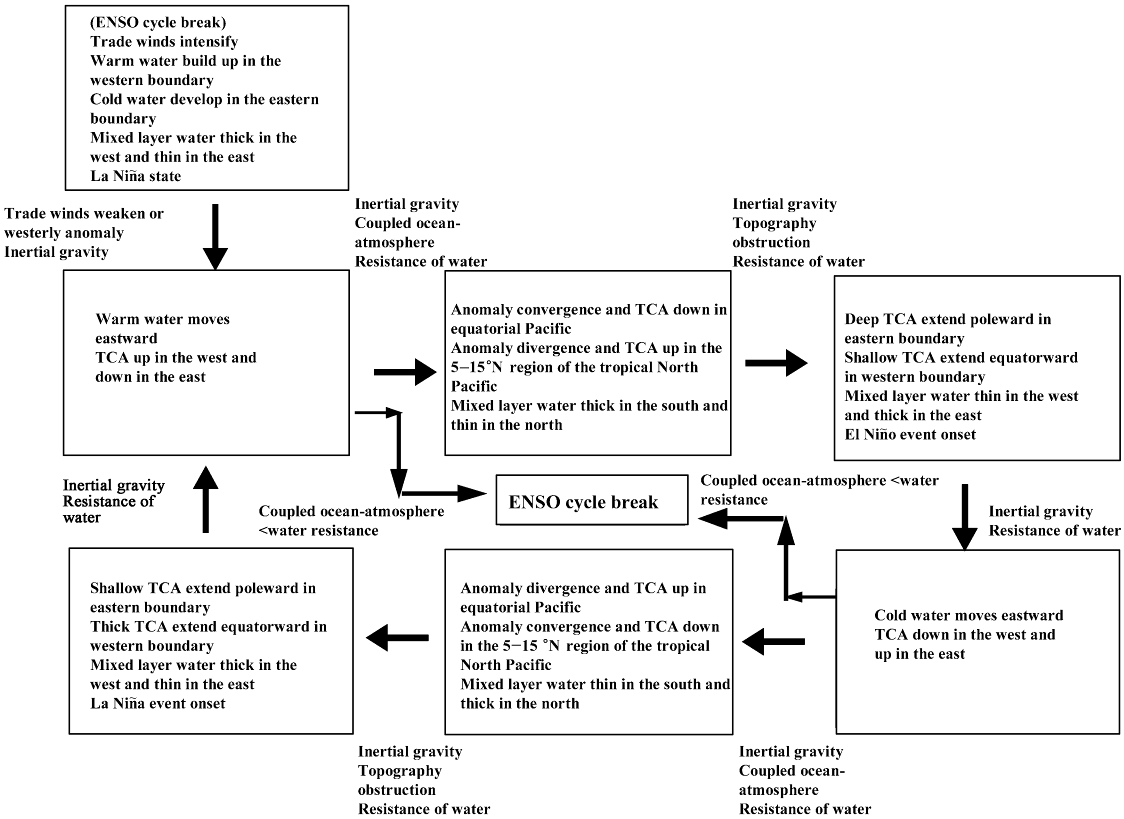

Figure 8 The tropical Pacific mixed layer water oscillation model for ENSO formation and cycle.

caused by the trade wind anomaly and the coupled ocean-atmosphere processes. The key processes are the trade wind anomaly and coupled ocean-atmosphere interaction, of which there are the following three ways to affect the ENSO cycle. The first is the trade wind anomaly keeping sea surface sloping in order to provide the initial potential energy for the mixed layer water oscillation. The second is the obvious WSA divergence fields in the equatorial Pacific and obvious opposite divergence fields in the 5—15°N region of the tropical North Pacific simultaneously for determining the route of the mixed layer water oscillation. The third is the coupled ocean-atmosphere interaction to intensify and maintain the motive force of the mixed layer water oscillation. In addition, it can be understood that the meridional propagation of the mixed layer water oscillation results from the topography obstruction in the western and eastern boundaries of the tropical Pacific.

7 Discussion and conclusion

To reveal the origin of warm or cold water of the western tropical Pacific, most of traditional models about the ENSO cycle so far are confined to the equatorial Pacific, or based on the "delayed oscillator" paradigm, or based on the simple model of the recharge and discharge of warm water in the upper ocean of the equatorial Pacific, however, the above models cannot accord well with the observations. In fact, the ENSO cycle is not only a marine phenomenon occurring in the equatorial Pacific, but also in the whole tropical Pacific. Generally, the subsurface temperature anomaly signal of the tropical Pacific propagating eastward along the equator is Kelvin waves, and that along 12°N of the tropical North Pacific is Rossby waves. But the observational data have shown that the moving speed of El Niño/La Niña event signals is slower than that of Kelvin waves along the equator and faster than that of Rossby wave along 12°N of the tropical North Pacific.

Why does the thermocline anomaly of the tropical Pacific propagate anticlockwise around the tropical Pacific basin between the equator and 12°N? Why does not this cycle appear in the south side of equator? The present results show that it has close relations to the special dominant wind field in the tropical Pacific. As is well known, the trade winds in the Southem Hemisphere is much stronger than that in Northem Hemisphere, the SE trade winds cross the equator and transit to S flow owing to the Coriolis' force. In this basic flow field, the dominant pattern of the WSA and its abnormal divergence field in the tropical Pacific represents the spatial distribution of the first mode shown in Figure 5. When the trade winds intensify, the abnormal easterly wind stress along the equator will induce the abnormal divergence there owing to the Coriolis' force, and the stronger cross equatorial S flow will cause convergence and induce abnormal convergence field in the 5—15°N region of the tropical North Pacific. Otherwise, when the trade winds weaken, the westerly WSA will induce the abnormal convergence field along the equator, and the abnormal equatorward N flow induces abnormal divergence field in the 5—15°N region of the tropical North Pacific, Which will result in the opposite phase of the WSA field between the equator and the off equator of the tropical North Pacific, and the opposite phase of thermocline anomaly between the equator and around 12°N of the tropical North Pacific, and finally form the tropical Pacific mixed layer water oscillation with anticlockwise route as shown by the measured data. It can be seen from Figures 3 and 4 that the mixed layer water reaching the eastern boundary of equatorial Pacific propagates northward and southward off the equator owing to the topography obstruction; on the other hand, because there are no strong enough NE trade winds crossing the equator from the Northern Hemisphere to the Southern Hemisphere, there are consequently no abnormal divergence fields opposite in phase along the equator in the tropical South Pacific. So that the thermocline anomaly signals extending to the south side of equator in the eastern boundary of the tropical Pacific will decay and disappear gradually and cannot form a cycle in the south side of equator.

According to the above mixed layer water oscillation model, the propagation speeds of the mixed layer water are nearly constant in different parts of the tropical Pacific during the cycle, from which it can be easily understood why the eastward speed along the equator is nearly equal to the westward speed along 12°N of the tropical North Pacific. Qiao et al.[37] also found out that the significant sea level height anomaly propagated westward fast in the subtropical North Pacific during the El Niño/La Niña cycle with its speed being faster than that of Rossby waves there. Actually, this westward propagation of sea level height anomaly is a response of the sea level height to the tropical Pacific mixed layer water oscillation.

Also, it can be easily explained why the amplitude and period of ENSO events have been increasing and the ENSO cycle has broken since the 1980s. The propagation speed of the mixed layer water is mainly dependent on the initial tilt of sea surface and the force produced by the coupled ocean-atmosphere interaction accompanied with the oscillation, and the former is the initial motive force of the water inertial oscillation, the latter is the motive force to overcome the water resistance for maintaining and intensifying the oscillation. In particular horizontal scale, it shows that the larger the amplitude, the longer the period. Owing to the climate shift since the end of 1970s, the strength of trade winds becomes much stronger, which causes the warm water buildup to be thicker for keeping equilibrium with stronger trade wind stress in the tropical western Pacific, and the period to be longer certainly. As far as the motive force maintaining the mixed layer water oscillation is concerned, the force produced by the coupled ocean-atmosphere interaction is too weaker to overcome the water resistance, the inertia gravity of the mixed layer water will weaken, and the oscillation amplitude will decrease, and even the oscillation ceases, which finally will induce the ENSO cycle to break.

To sum up, the essential of ENSO cycle is the tropical Pacific mixed layer water oscillation with anticlockwise route around the tropical Pacific basin between the equator and 12°N, which is caused by the trade winds anomaly and the coupled ocean-atmosphere interaction. The trade wind anomaly induces the sea level tilt and provides the initial potential energy for the mixed layer water oscillation, in the meantime it induces the opposite significant anomaly divergence fields along the equatorial Pacific and in the 5—15°N region of the tropical North Pacific simultaneously, therefore determines the route of the mixed layer water oscillation. The coupled ocean-atmosphere interaction provides the motive force for maintaining oscillation and overcoming water resistance. The water oscillation and the coupled ocean-atmosphere interaction provide the phase-switching mechanism and the interannual memory for ENSO cycle. ITCZ has some influence on the phase switching during the ENSO cycle.

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