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RELATIONSHIP BETWEEN INTERANNUAL VARIATION OF MERIDIONAL WIND ANOMALIES IN TROPICAL PACIFIC AND SSTA

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ABSTRACT: The Singular Spectrum Analysis (SSA) method is used to conduct studies of periodicity of the SST and meridional winds in tropical Pacific Ocean. The results show that the air-sea system for the Pacific varies on quasi-4-year, quasi-2-year and interannual scales, with the quasi-4-year scale having the highest variability. Depending on the scale, the wind field has a varying degree of association with the SST anomalies. Difference is also found in the evolution of phase. In addition, the work discusses the difference in SSTA resulted from wind fields for quasi-4-year and quasi-2-year components.

Key words: air-sea interactions; ENSO; SSA

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1 INTRODUCTION

ENSO is one of the strongest signals yet that has been observed for interactive coupling between the atmosphere and ocean across the globe. A forthcoming ENSO will have consequent effects on climate over many parts of the world, thus becoming a primary factor to consider in climate prediction in large number of countries. It is therefore particularly important to deepen the understanding of the ENSO cycling and to recognize any precedent signals for the onset of ENSO.

Owing to a series of classic works of Bjerknes[1-3] back in the middle of 1960's, study on the interaction between the atmosphere and ocean has been greatly carried forward. The concepts of El Niño and SO are in fact two facets of a single phenomenon —large-scale air-sea interactions taking place over the tropical Pacific Ocean. In the opinion of Rasmusson[4], the ENSO variation is composed of three components of varying time scale, i.e. annual cycle, quasi-2-year oscillation and low-frequency component of 3 to 4 years or longer, with the latter having the highest peak value. From the viewpoint of interactions between monsoon and ENSO, Yasunari[5] puts forward that there is a quasi-2-year cycle in the air-sea coupling in tropical monsoon. Recently, He et al[6]. work on the seasonal change and mutual relationship in air-sea interactions over the equatorial eastern Pacific and Indian Ocean. It is then known that the characteristics of tropical air-sea interactions on different time scales are still one of the hot topics today.

In their study on ENSO's anomalous characteristics of tropical atmosphere and ocean for various phases from generation to dissipation, Rasmusson et al.[7] conclude that westerly anomalies are an absolutely necessary prerequisite for causing the El Niño. Inconsistent views

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Biography: ZHANG Zu-qiang (1971 –), male, native from Guizhou Province, assistant professor, Ph.D., mainly undertaking the study on air-sea interactions and monsoon dynamics.

remain on the origin of westerly. With an analysis of evolution of tropical wind fields prior to individual El Niño events between 1958 and 1997, Zhang et al.[8] identify the convergence of meridional winds in western Pacific as the main driving force for the onset and eastward propagation of equatorial westerly, with the austral southerly being stronger. It keeps staying over waters east off Australia and is active throughout the whole life cycle of El Niño. The air current originates from the mid-and-high latitudes of the Southern Hemisphere, representing the effect of middle-latitude pressure systems on the El Niño. It prompts us to continue probing into the evolution of longitudinal convergence in eastern Pacific and its effect on the equatorial SST so as to reveal how the longitudinal convergence across the eastern and western Pacific are coordinating in the ENSO cycle.

2 DATA AND BRIEF INTRODUCTION TO SSA

The work uses the NCEP / NCAR monthly mean reanalysis data for global wind field that covers 1958 ~ 1959. The SST field comes from the Wisconsin University (1958 ~ 1981) and NCEP' s 1°×1° objective interpolations over global ocean surface (Jan. 1981 ~ Aug.1998).

SSA is a method that analyzes periodicity in one-dimensional time series. Given maximum time lag M (window length), we are able to derive Toeplitz matrix constructed with the function of auto-covariance difference for different lagging time of 0, 1, …, M, before determining its characteristic value and vector. On the basis of it, we can obtain the periodicity of the original series and its variance contribution. The processes presented above are actually equivalent to applying time empirical orthogonal function (TEOF) of the time-lagging matrix of that time series. It can be proved that the TEOF of time-lagging matrix is also equivalent to singular value decomposition (SVD) treatment. That is how the term SSA comes about. Compared to power spectrum, SSA is of generalized spectrum. For power spectrum, time series is viewed as discrete samples of oscillations, which are superimposed with sinusoidal waves of varying frequencies. For SSA, however, assumption of sine relation is not needed and wave-form signals recognized by it are not necessarily sinusoidal waves. They are immediately determined by actual series and can amplify and enhance any signals of power spectrum. It is then known that periodicity identified with SSA is so accurate that any two consecutive spectral peaks are distinguished while what can be achieved with power spectrum is nothing more than mean periodicity.[9].

3 ANALYSIS OF INTERANNUAL VARIABILITY OF SST AND LONGITUDINAL WIND

3.1 *Niño 3 index*

As the focus of the study is on the interannual variation of SST, the window length is set at 120 months for SSA analysis of the Niño 3 index (figure omitted). Depending on the magnitude of variance contribution, major components of oscillation in the index include 3.5 yr (32.6%), 4.5 yr (17.4%), 2.5 yr (12.5%) and 2 yr (8.0%). It is then clear that SSA is indeed a good method for periodicity study in time series. The resolution is high while the traditional way of power spectrum is capable of resolving mean periodicity at 4 yr and 2 yr only. Another function of SSA is to reconstruct series for individual major oscillating components. Fig.1 gives the sum of reconstructed series for four major interannual oscillating components of the Niño 3 index and fitting of original series. Two curves vary consistently, showing that the variation components of the four time scales are adequate enough to replace the Niño 3 index, i.e. the interannual variation of SST in the equatorial central and eastern Pacific.

3.2 *Longitudinal convergence in western Pacific Ocean*

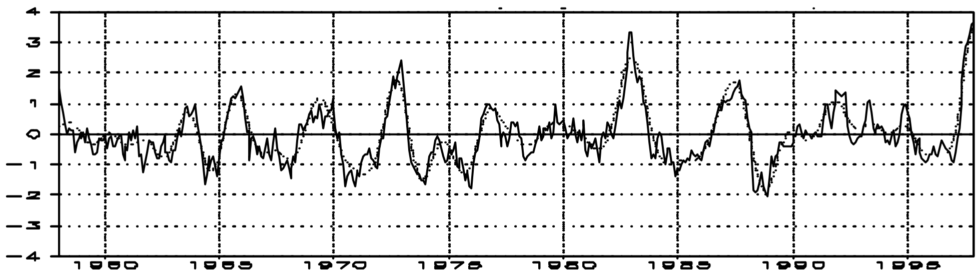

Fig.1 Fitting between the sum of major interannual reconstructed components of Nino 3 (dotted line) and the normalized Nino 3 index (solid line).

In a way the same as [8], SSA is performed of the difference in longitudinal wind anomalies with convergence intensity being the regional average over 20°S ~ 5°S, 137°E ~ 170°E and 5°N ~ 20°N, 120°E ~ 160°E in western Pacific.

Arranged in the order of decreasing variance contribution, the principal oscillating components of longitudinal convergence in western Pacific are 4 yr (17.5%), 2.5 yr (15%), 3.5 yr (11.3%), interdecadal (11.1%) and 2 yr (6.3%). The accumulative variance is 61.2% for first 10 eigenvectors. As the SST is dominated with 2-to-5 yr oscillations in central and eastern equatorial Pacific, the work will focus on analyzing fluctuations on the time scale.

By combining the 4-yr component with the 3.5-yr one and the 2.5-yr component with the 2-yr one, quasi-4-yr and quasi-2-yr variations can be represented. Fig.2 compares the reconstructed series and components rebuilt on corresponding scales of the Niño 3 index. The result shows that longitudinal convergence for the two scales are generally in phase with the Niño 3 index, though by a little leading. For relatively strong El Niño years, however, the quasi-4 and quasi-2 yr oscillations of longitudinal convergence are much stronger in western Pacific, in high simultaneity. In general, the quasi-4-yr oscillation is stronger than the quasi-2-yr one but the components of the latter in 1997 is larger than the former in terms of variance contribution.

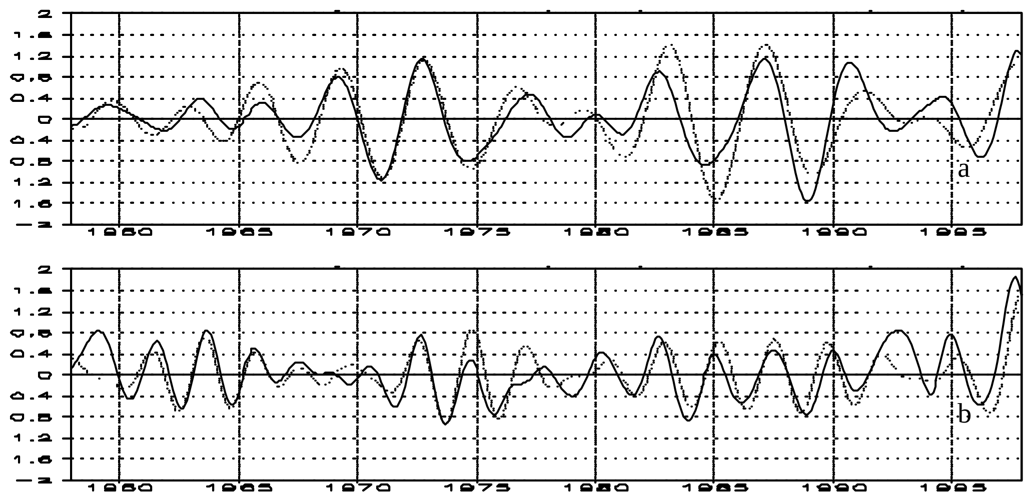

Fig.2 Comparison of the major reconstructed components between longitudinal convergence anomalies over western Pacific(solid line) and El Niño 3 index (dashed line). a. Quasi-4-yr component; b. Quasi-2-yr component.

It is then seen that for the western Pacific longitudinal convergence, principal interannual oscillating components vary consistently with the El Niño index. It is another footnote to the main argument of [8] that the longitudinal convergence in western Pacific is closely linked with El Niño. The longitudinal convergence is one of the main conditions for the outburst and eastward propagation of westerly and the eastward propagation is a necessary condition for triggering the El Niño.

3.3 *Longitudinal wind in tropical northeastern Pacific Ocean*

Climatologically, there are two longitudinal airflows from middle latitudes in eastern Pacific —the northeasterly and southeasterly trades. Over the early period of El Niño onset, the trade weakens in eastern Pacific. Wyrtki[10] thinks that it is its increase / decrease that results in alternative appearance of El Niño and La Niña. For the purpose, the current section is used to conduct SSA for the anomalies of longitudinal wind that is regionally averaged over 5°N ~ 20°N, 160°W ~ 110°W and compare the corresponding relationship between its reconstructed components and Niño 3 components.

As shown in the analysis, variations of northeasterly trade take place mainly on four scales — interdecadal (13.0%), quasi-6-yr (13%), quasi-4-yr (11.2%) and quasi-2-yr (7.1%). On the quasi-4-yr scale, the northeasterly trade is roughly in negative correlation with the Niño 3 index, though having some phase difference between them. In Fig.3, the Niño 3 index turns positive from negative usually around the peaks of northeasterly trade, i.e. when the northerly weakens to its minimum or the southerly increases to its maximum. When the northeasterly trade strengthens, however, the positive anomalies are the highest for Niño 3. In comparison, the northeasterly trade has the smallest amplitude regarding the quasi-2-yr component and is also unstably linked to the variation of the Niño 3 index.

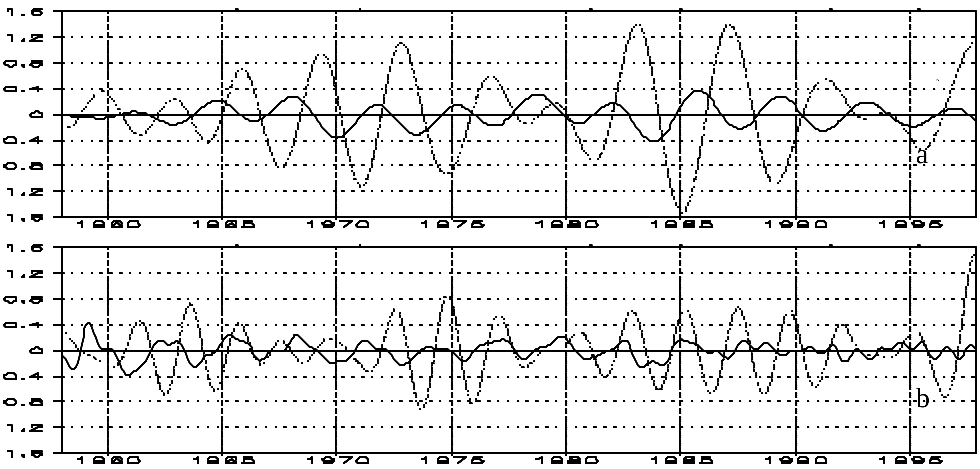

Fig.3 Same as Fig.2 but with wind field being longitudinal anomalies in tropical northeastern Pacific (5°N ~20°N，160°W ~ 110°W).

3.4 *Longitudinal wind in southeastern Pacific Ocean*

In this work, the southeasterly trade intensity is depicted using the longitudinal wind regionally averaged over 20°S ~ 5°S, 120°W ~ 80°W. The primary periodicity in the variation of the trade include interdecadal (21.4%), quasi-4-yr (16.3%), quasi-2-yr (8.7%) and quasi-8-yr

(5.3%). Fig.4 is the comparison between their reconstructed series and corresponding components of the Niño 3 index. They are negatively correlated on the quasi-2-yr and quasi-4-yr scales, with the peak of one scale just coinciding with the valley of the other. Vice versa. In other words, when the southeasterly trade increases to the maximum, the Niño 3 index would get to a maximum negative anomaly, signaling the arrival of the prime season of La Niña. In contrary, the southeasterly trade will weaken, as SST is positively anomalous.

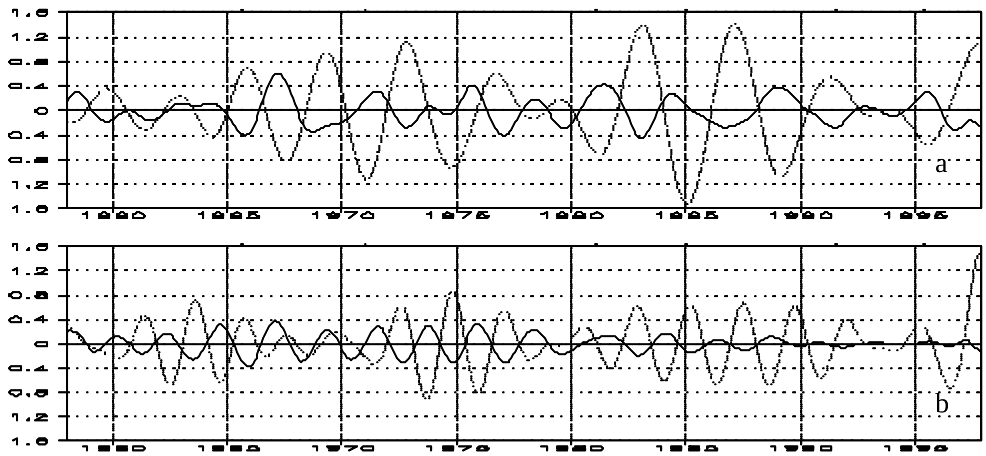

Fig.4 Same as Fig.2 but with wind field being longitudinal anomalies in tropical southeastern Pacific (20°N ~ 5°N, 120°W ~ 80°W).

With all these Singular Spectrum Analysis of longitudinal wind series for both eastern and western Pacific, it is now known that the convergence intensity of western Pacific longitudinal wind is in good agreement with the evolution of phase of the Niño 3 index on quasi-4-yr and quasi-2-yr scales. It is not only shown in wind field varying consistently with reconstructed series of SST but in identical order of variance contribution by oscillations of individual scales to original series. Of the time scales, the quasi-4-yr one is the strongest, followed by the quasi-2-yr one. In contrast, the longitudinal wind in eastern Pacific is poorly linked with the Niño 3 index, nor is the quasi-2-yr northeasterly trade well connected with its variation. It is, however, worth noting that it keeps stable phase difference with the index on the quasi-4-yr scale —it is usually the case that a weakening northeast trade is accompanied by the change of the index from negative to positive and rise in SST in central and eastern Pacific. When positive SST anomaly accumulates to some extent, northerly wind will increase in the northeasterly trade area due to forcing effect of local heating source.

4 CORRELATION BETWEEN INTERANNUAL VARIATION COMPONENTS OF TROPICAL LONGITUDINAL WINDS AND SST

In the previous sections, the close links between the quasi-4-yr and quasi-2-yr longitudinal winds and SST in the Niño 3 region are studied. The current section will deal with the correlation patterns between reconstructed components of longitudinal wind on various time scales and global SST and attempt to discuss varying links between wind field components on the scales and SST.

4.1 *Longitudinal convergence in western Pacific*

Fig.5 gives longitudinal convergence in western Pacific in simultaneous correlation with global SST on the quasi-4-yr and quasi-2-yr scales. It is shown that there is much similarity between the two scales. When the longitudinal convergence strengthens in western Pacific, the SST will decrease in western tropical Pacific and middle-latitude waters but increase in central and eastern Pacific, in addition to positive anomaly of SST in the part of the Indian Ocean north of 10°S. It reflects how the SST distributes during the mature stage of El Niño. The fact that the correlation on the quasi-4-yr scale is higher than the quasi-2-yr one and with an eastward location of correlation center accounts for closer simultaneous relationship on the former scale between the Pacific SST and longitudinal convergence in western Pacific and more to the eastern Pacific in terms of the SST anomaly location that is triggered.

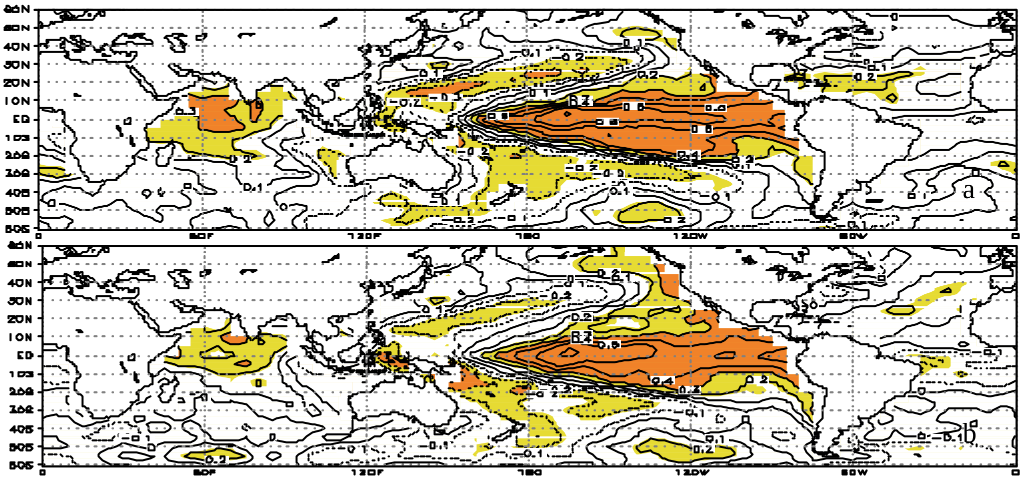

Fig.5 Simultaneous correlation between longitudinal convergence over western Pacific and SST. The shaded regions indicate the correlation coefficient passing the 95 % confidence level. a. Quasi –4-yr component; b. Quasi-2.5-yr component.

4.2 *Longitudinal wind in northeastern Pacific*

For the longitudinal wind in northeastern Pacific, the quasi-4-yr reconstructed component is negatively, weakly correlated with the SST in eastern Pacific while the quasi-2-yr one is almost independent of it. As shown in the results from Section 3.3, the longitudinal wind varies with SST out of phase on the scale. To clarify the problem, the longitudinal wind is calculated for its monthly cross correlation of the SST by leading / lagging 24 months. Fig.6 gives the distribution of correlation coefficients for longitudinal wind leading or lagging by 12 months. When SST leads by 18 ~ 12 months, the longitudinal wind is positively correlated with it in central and eastern Pacific but the correlation is greatly decreased when the leading drops to 6 months. When the lagging is between 0 and 12 months, correlation is negative and strong before weakening again and transforming to positive value. It shows that 12 to 18 months after the northerly weakens, the SST would usually rise in the equatorial central and eastern Pacific and the atmosphere is heated by warmed seawater to cause convergence at low levels. It in turns results in the strengthening of the northerly.

4.3 *Longitudinal wind in southeastern Pacific*

Fig.7 gives the simultaneous correlation between the annual variation components of longitudinal wind in southeastern Pacific and SST. The results show that the quasi-4-yr and

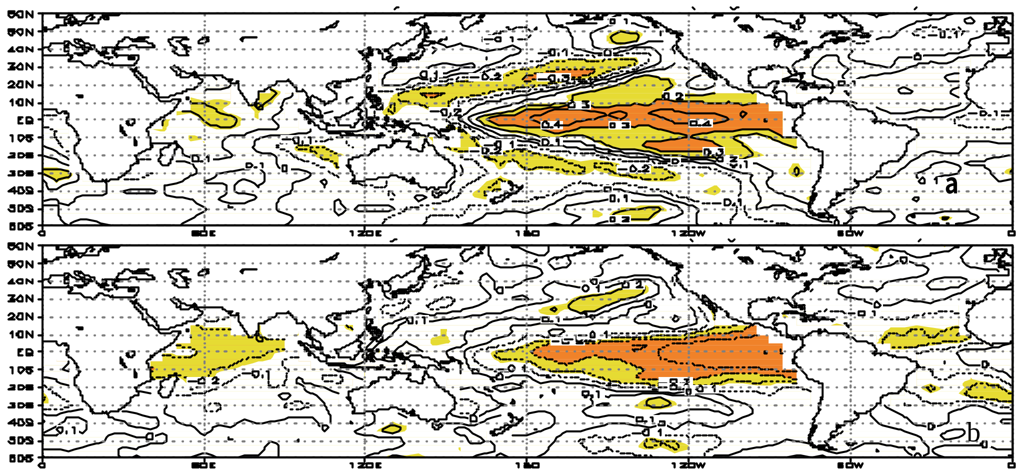

Fig. 6 Cross correlation between the quasi-4-yr component of longitudinal wind over north-eastern Pacific (5°N ~ 20°N, 160°W ~ 110°W) and SST. a. longitudinal wind leading 12 months; b. longitudinal wind lagging 12 months. The shaded regions indicate the correlation coefficient passing the 95 % confidence level.

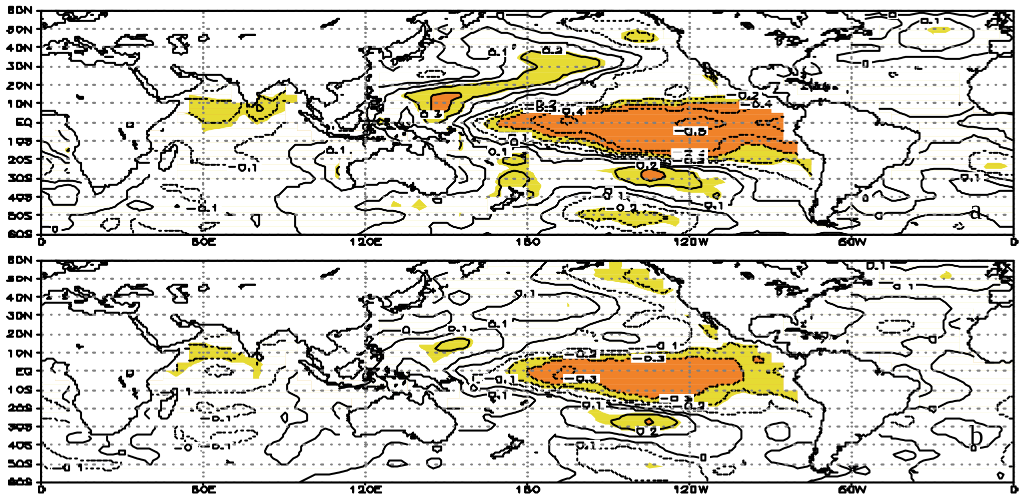

Fig.7 Simultaneous correlation between longitudinal wind over southeastern Pacific (5°S ~ 20°S, 120°W ~ 80°W) and SST. a. Quasi-4-yr component; b. Quasi-2-yr component.

quasi-2-yr components have relatively small variance contribution, but they are in high negative correlation with the SST in equatorial eastern Pacific. It is shown that the longitudinal components for the scales are weakening in association with the increase of SST in eastern Pacific, with the correlation center locating in eastern Pacific that corresponds to the former component while the response from the quasi-2-yr component comes from central Pacific.

Summarizing the analysis of the current section, we know that the relationship between longitudinal airflow in eastern and western Pacific and SST is very complicated —varying according to the location of the wind field and time scale. The primary periodicity in the Pacific air-sea couplings is the quasi-4-yr one, which is significant in the relationship between longitudinal wind and SST in both eastern and western ends of the ocean, though with different evolution of phase. The correlation is largely simultaneous or slightly leading between northwestern / southeastern Pacific and the SST, staying within the positive territory. They are inconsistent in northeastern Pacific, with 1/4 ~ 1/3 phase in leading (12 ~ 18 months), being in negative correlation. On the quasi-2-yr scale, however, the correlation is close for western or southeastern Pacific while it is not significant for northeastern Pacific.

5 QUASI-4-YR AND QUASI-2-YR MODES OF AIR-SEA SYSTEM IN TROPICS

As shown in correlation analysis, the center of SST correlation for the wind field on quasi-4-yr scale is situated over eastern Pacific while that on quasi-2-yr scale over the equatorial central Pacific. To confirm the difference, the SST components at 3.5 yr and 2.5 yr are selected in phase composition band-filtered wind field and SST field.

By phase composition, a cycle of ENSO is divided into nine phases. The first phase depicts the initial stage of El Niño, the third phase the mature stage and the fifth phase the time when positive SST anomalies in eastern Pacific weaken to normal level and change to negative anomalies. La Niña enters a time of maturity in the seventh phase and cold seawater disappears in the ninth phase. The second, fourth, sixth and eighth phases in between represent respectively the relaying stages of development or dissipation of El Niño or La Niña. Following the 3.5-yr and 2.5-yr components reconstructed from SSA of the Niña 3 index, the time with the above nine phases are determined. The SST and simultaneous wind field are then composed through filter. Fig.8 gives composition of SST and wind fields for the first, third and fifth phases, reflecting the life cycle of El Niño, which initiates, develops, maturates, weakens and decays.

Fig.8 shows that the links are very close between the 3.5-yr-scale SST and wind field anomalies. In the initial phase of warm SST (Fig.8a), the advection effect of wind stress on cold water in high latitudes are weakening and positive SST anomalies appear over low-latitude Pacific north of the equator as northerly weakens in the area of northeasterly trade. It is around the time that longitudinal convergence is produced over western Pacific and westerly begins to expand eastward north of the equator. In the second phase (of development, figure omitted), convergence further strengthens in western Pacific to force the westerly to burst out strongly to the east, resulting in rapid rise of SST in central and eastern Pacific. The phase also sees the weakening of southerly in southeastern Pacific and re-strengthening of northerly in northeastern Pacific under the forcing of local warm SST. In the mature phase (Fig.8b), convergence reaches the maximum in western Pacific and El Niño is at its fullest wing, maintaining the increase of northerly in northern Pacific and strong negative anomalies of the southeasterly trade. In the fourth phase (of dissipation, figure omitted), the convergence weakens in western Pacific, equatorial westerly reduces but the northerly anomalies remain strong in northern Pacific and SST begins to drop north of the equator. In the phase of decaying (Fig.8c), positive SST anomalies weaken and withdraw to areas south of the equator and easterly prevails due to the effect of enhanced northeasterly trade, being favorable for the generation of cold phase that comes subsequently.

For the evolution described above, the SST anomalies develop from north to south in central and eastern Pacific. Positive anomalies first appear in areas north of the equator and the order is the same with the decrease and decaying. It is associated with the advection effect of intensity change of northeasterly trade on SST. In addition, the equatorial westerly, acting as a key factor in triggering the El Niño, is present over the entire Pacific Ocean from the first to second phases, with the maximum center locating near 130°W and positive SST anomalies over eastern Pacific at 120°W, which extends westward to 160°E.

The quasi-2.5-yr air-sea system evolves in much the same way as the quasi-3.5-yr one in

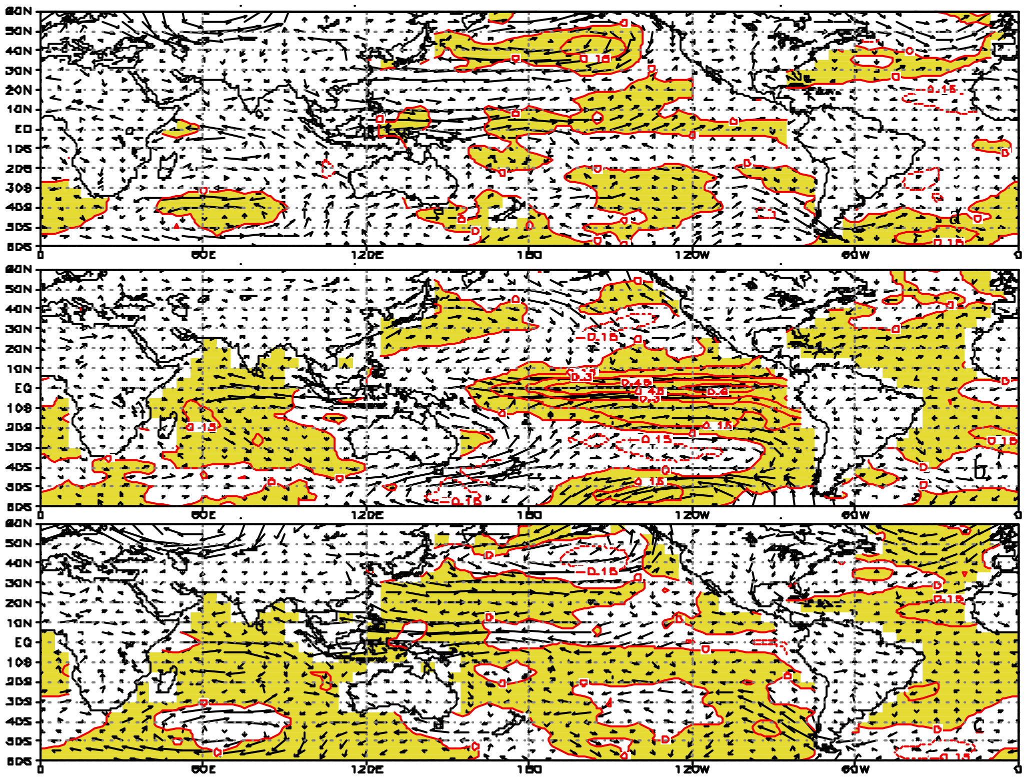

Fig. 8 Phase evolution of quasi-3.5-yr SSTA and 850 hPa wind and the first, third and fifth phases are shown in (a) to (c). The regions of the positive SSTA are shaded.

that in central and eastern Pacific SST rises with the eastward propagation of westerly but falls with the reduction of westerly. They differ from each other in the following two points. Firstly, the longitudinal intensity is weaker in western Pacific in Fig.9 than in Fig.8. Secondly, weaker westerly is generated that borders near 170°W only, with the center much more westward than the 3.5-yr air-sea system and the easterly anomaly covering areas east of 120°W. It is then known that the intensity of quasi-2.5-yr SST anomaly is relatively weak with the center over central equatorial Pacific. SST evolves in different directions for the quasi-2.5-yr and quasi-3.5-yr scales. As shown in the figure, the southeastern Pacific trade much reduces right from the initial stage, leading to first appearance of positive SST anomaly on the coast of South America. Then, with the eastward propagation of westerly, positive SST anomaly develops in the equatorial region. It is also along the South America coast that warm SST dissipates. It is resulted from the fact that the re-strengthened southeasterly trade has caused complete disappearance of positive anomalies over southeastern Pacific while they are still present on the North American coast. It is therefore decided that the quasi-2.5-yr SST anomaly advances from south to north in the cycle of development and dissipation, which is just the opposite from the evolution on the quasi-3.5-yr scale. It may be caused by more significant effect of longitudinal wind over the southeastern Pacific for the quasi-2.5-yr scale while longitudinal airflow contributes more over the northeastern Pacific for the quasi-3.5-yr scale. The intensity of longitudinal wind in northern Pacific is much reduced in Fig.9 than in Fig.8.

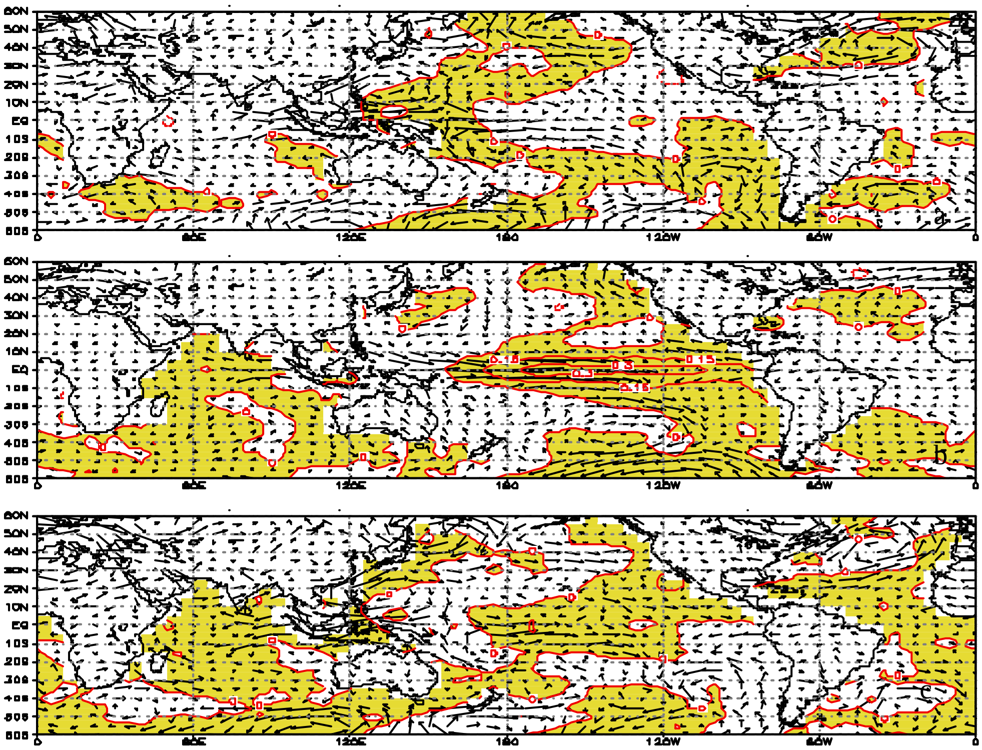

Fig.9 Same as Fig.8 but for the quasi-2.5-yr component.

6 CONCLUDIG REMARKS

a. With the method of SSA, Periodicity analysis is carried out for longitudinal wind and SST in both eastern and western tropical Pacific regions. Results have indicated that the Pacific air-sea system varies on quasi-4-yr, quasi-2-yr and interdecadal scales, with the first being the strongest. As far as relative intensity is concerned, the variability of quasi-2-yr scale becomes larger than that of quasi-4-yr scale starting from the 1990's, leaping to become the tendency for primary periodicity in the interannual variation of El Niño 3 index.

b. Wind fields are variably linked with SST depending on location and time scale and so is the evolution of phase. Longitudinal convergence is in high positive correlation with SST on all scales, being generally simultaneous with or a little leading the change in SST.

For the longitudinal wind in the northeasterly trade region, the quasi-4-yr component leads the central / eastern Pacific SST by 1/4 ~ 1/3 phase and they are negatively correlated. When the quasi-4-yr and quasi-2-yr components of longitudinal wind decrease in the southeasterly trade region, SST rises in eastern Pacific. The center of the waters responding to the former component is found in eastern Pacific while waters responding to the quasi-2-yr component appear in central Pacific.

c. Differences between the wind fields above and SST variation are the immediate cause for the difference of SST between the quasi-4-yr and quasi-2-yr scales. Relatively speaking, longitudinal convergence is stronger with the former scale, which triggers westerly that circles the entire region of equatorial Pacific, causing more eastward location of SST anomalous center than the latter scale. As the longitudinal winds are closely linked to SST on the former scale over the northeasterly trade region, anomalies will be resulted in seawater advection when anomalous wind field appears. The anomalies of SST first appear north of the equator and then progress southward. For the quasi-2-yr scale, the southeasterly trade plays a more dominant role so that SST anomalies develop northward.

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