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Meridional Wind Stress Anomalies over Tropical Pacific and the Onset of El Niño. Part I: Data Analysis①

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ABSTRACT

By using correlation analysis and singular value decomposition (SVD) methods, diagnostic studies are made to investigate the relationship between the meridional wind stress anomalies over the tropical Pacific and El Niño events. The correlation of the sea surface temperature anomalies (SSTA) in the NINO3 region (150°–90°W, 5°S–5°N) and the leading meridional wind stress anomalies shows that the NINO3 SSTA is significantly correlated with the anomalous meridional wind stress convergence in the equatorial eastern Pacific at the leading time of more than six months. With the reduction of the leading time, the correlation becomes stronger and the convergence area with statistical significance enlarges and extends to the west. The coupling patterns between SSTA in tropic Pacific and the leading meridional wind stress anomalies revealed by SVD show the similar feature to that revealed by the correlation analysis. The converging meridional wind stress about the equator in the eastern equatorial Pacific precedes the increasing of SSTA in the central and eastern equatorial Pacific as early as half a year or more. Compared to the leading zonal wind stress anomalies in the tropical western Pacific, it seems that the increasing of the NINO3 SSTA is more related to the convergence of the leading meridional wind stress anomalies in the eastern equatorial Pacific. It is suggested that preceding meridional wind stress anomalies may play an important role in the occurrence of El Niño events.

Key words: Meridional wind stress, El Niño

1. Introduction

An El Niño is the period when the ocean temperature of upper layer in the central and eastern equatorial Pacific rises abnormally. The movement of the tropical upper layer ocean is driven mainly by wind stress. The formation of the mean state of the tropical upper layer ocean is closely related to the atmospheric wind stress, and the occurrence of an El Niño is associated with the atmospheric wind stress anomalies. A lot of researches have been done to investigate the role of the atmospheric wind stress on El Niño (e.g., Wyrtki, 1975; Philander, 1981, Rasmusson and Carpenter, 1982; Weisberg and Tang, 1984; Huang and Zhang, 1997; Zhang and Huang, 1998). All these researches have pointed out the importance of the zonal wind stress anomalies during the El Niño episode through the data diagnosis, dynamic analysis and the numerical simulation, respectively.

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Up to now, the studies have mainly emphasized the effects of the zonal wind stress anomalies on an El Niño. McCreary (1976) pointed out that the meridional wind stress anomalies are not important to an El Niño because they cannot excite the oceanic Kelvin wave, which is of central importance to El Niño events. However, the studies by Philander and Pacanowski (1981), Yamagata and Philander (1985) and Xie (1994) demonstrated that the meridional wind stress were important to the formation of the climatology, seasonal variations and annual cycle of the equatorial Pacific Ocean. Therefore, it can be inferred that the anomalies of the meridional wind stress should cause the anomaly of the mean state of the equatorial ocean.

In fact, some observational studies (e.g., Hickey, 1975; Philander, 1983) showed that one of the precursors of an El Niño is that ITCZ moves southward abnormally from its climatological position of about 9°N to 3°N or even near the equator. The abnormally southward moving of ITCZ should accompany the anomalies of the meridional wind stress field. The results of numerical experiments by Philander and Pacanowski (1981) indicated that the relaxation of the meridional wind stress can change the climatology of tropical ocean and cause the variation of the zonal distribution of heat in the ocean. Therefore, the meridional wind stress anomalies in the central and eastern equatorial Pacific should have important effects on the occurrence of El Niño events.

Harrison (1989) studied the local and remote forcing of the wind stress on the 1982–83 El Niño event by using an oceanic model. In his model experiments, when the meridional wind stress is omitted, but the zonal wind stress is retained within 7° of the equator, the model reproduces upper–ocean dynamic height acceptably, but introduce errors in sea surface temperature (SST) and upper–ocean currents that approach the ENSO signal. He pointed out that the meridional wind contributed nontrivially to model near equatorial behavior during the 1982–1983 ENSO event. However, the role of the meridional wind stress in the occurrence of ENSO and how the meridional stress affects the ENSO are still unclear. In order to go further insight into the physical mechanisms of the occurrence of an El Niño, it is necessary to investigate the effects of the meridional wind stress anomalies on El Niño events.

This paper is the first part of this study. Through analyzing the observational data, the relations of the meridional wind stress anomalies in the tropical Pacific with SSTA associated with El Niño will be investigated. In Section 2 the data and analysis methods are described. The correlation between the meridional wind stress over the tropical Pacific and the SSTA in the equatorial eastern Pacific is analyzed in Section 3. Section 4 discusses the coupling patterns between the meridional wind stress anomalies and SSTA in the tropical Pacific by using the SVD method. In Section 5 a comparison of the zonal and meridional wind stresses on the occurrence of the El Niño events is given. The summary and concluding remarks follow in Section 6.

2. Data and analysis methods

The data used in the present paper are the monthly mean sea surface wind stress data set compiled by Florida State University (FSU) on a $2^\circ \times 2^\circ$ grid over the area of tropical Pacific 29°S–29°N, 124°E–70°W from January 1961 to June 1989. The global monthly mean sea surface temperature (SST) data set provided by the Japan Meteorological Agency (JMA) on a $2^\circ \times 2^\circ$ grid from January 1946 to August 1994 is also used. The SST data in the same period as wind stress data set are utilized in the analysis. The analysis methods used in the paper are correlation and SVD analyses.

3. Correlation between NINO3 SSTA and the meridional wind stress anomalies

In order to analyze the relationship between El Niño events and the meridional wind stress, based on the method of Zebiak and Cane (1987), an region called NINO3 (5°S–5°N, 90°–150°W) in the eastern equatorial Pacific is selected. The SSTA averaged over the NINO3 region acts as the proxy of the change of SSTA in the eastern equatorial Pacific associated with El Niño events. Figure 1 shows the time evolution of the monthly NINO3 SSTA. It can be seen clearly that the positive peaks of the NINO3 SSTA indicate well the El Niño events. We also can see from Fig. 1 that there are 7 El Niño events in the data period. They occurred in 1963, 1965, 1969, 1972, 1976, 1982/83 and 1986/87, respectively.

Figure 2 shows the correlation coefficients between the NINO3 SSTA and meridional wind stress prior to NINO3 SSTA by seven months (Fig. 2a), five months (Fig. 2b), three months (Fig. 2c) and one month (Fig. 2d) as well as at the same time (Fig. 2e), respectively. The shadings in Fig. 2 are the areas with statistical significance at 95% level. Corresponding to a positive NINO3 SSTA or SST rising in the NINO3 region, the positive and negative correlation coefficients in Fig. 2 represent the southerly and northerly wind stress anomalies, respectively.

When the meridional wind stress is prior to NINO3 SSTA by seven months (Fig. 2a), it can be found that in the equatorial eastern Pacific between 80°–150°W, the negative correlation appears to the north of about 2°N and the positive correlation around and to the south of the equator. It is indicated that in seven months before the NINO3 SSTA rising, there appear northerly wind stress anomalies in the north of the equator and southerly wind stress anomalies in the south of the equator. The meridional wind stress anomalies converge about the equator in the eastern equatorial Pacific although the converging area of statistical significance is small and is confined near the equator. Meanwhile, another significant area of positive correlation can be found to the northeast of Australia.

When the meridional wind stress is prior to NINO3 SSTA by five months (Fig. 2b), both the negative correlation area to the north of equator and the positive correlation area to the south of equator in the equatorial eastern Pacific showed in Fig. 2a become larger and expand westward. The converging area stretches to the dateline and the correlation becomes stronger. The positive correlation area to the northeast of Australia also strengthens. The correlation coefficients prior by three months and one month are shown in Figs. 2c and 2d, respectively. The negative correlation area to the north of equator and the positive correlation area to the south of equator enlarge continuously. And the correlation coefficients are also intensified. The areas with statistical significance in the tropical eastern Pacific become larger and the anomalous convergence becomes much stronger. There exists fairly strong converging area about the equator. In the meantime, the positive correlation area of statistical significance to the northeast of Australia appears between about 20°S–0° and extends to the central Pacific, which, together with the northerly wind stress in the north of equator, forms another abnormally convergent area in the central and western equatorial Pacific. The simultaneous correlation between NINO3 SSTA and the meridional wind stress is shown in Fig. 2e. The converging areas are more significant. At this time, the anomalous convergence of the meridional wind stress almost appears in the whole equatorial Pacific.

From the above correlation analyses, it can be seen that in the central and eastern equatorial Pacific there is significant correlation between NINO3 SSTA and leading meridional wind stress anomalies converging near the equator. In seven months before El Niño events,

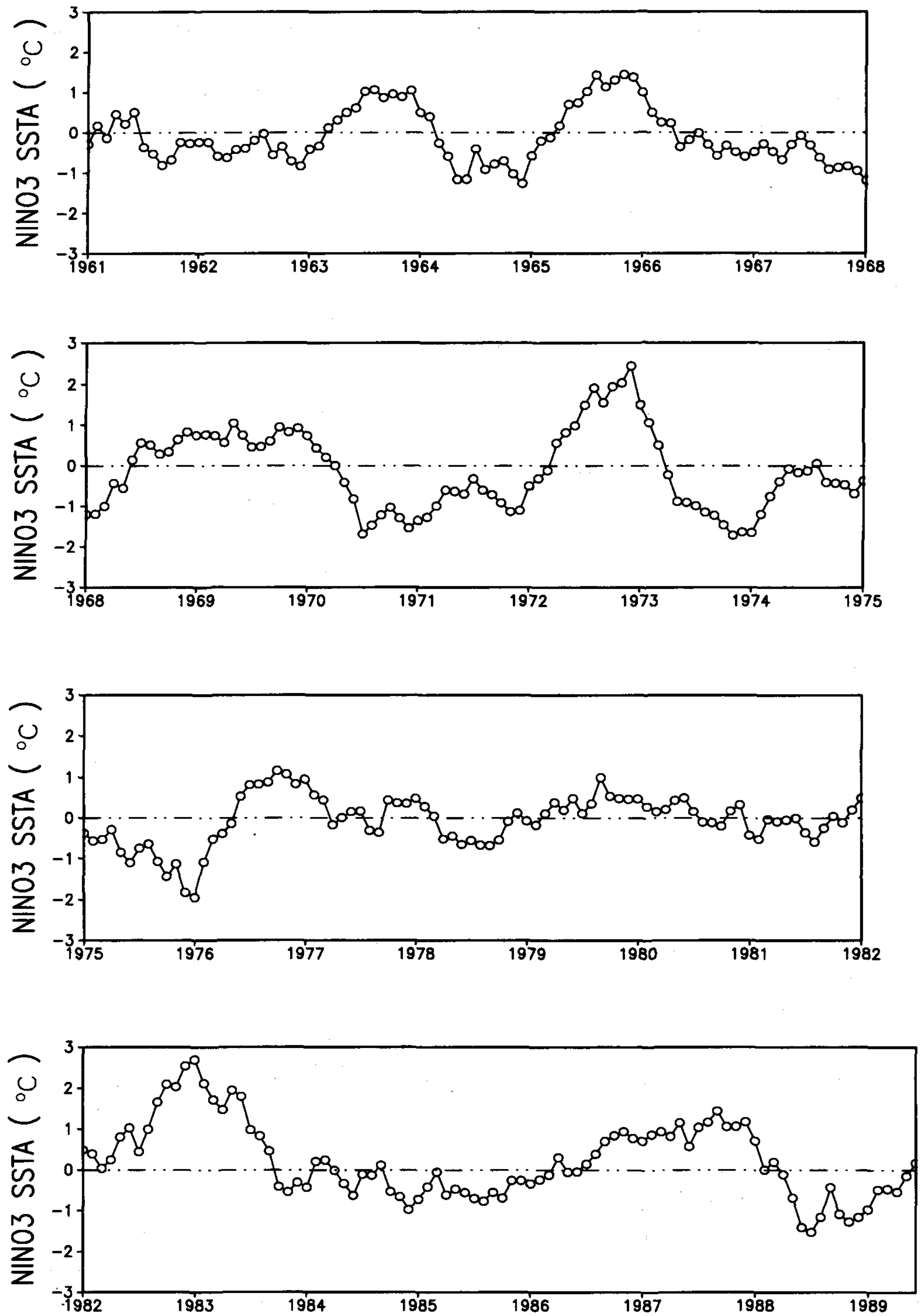


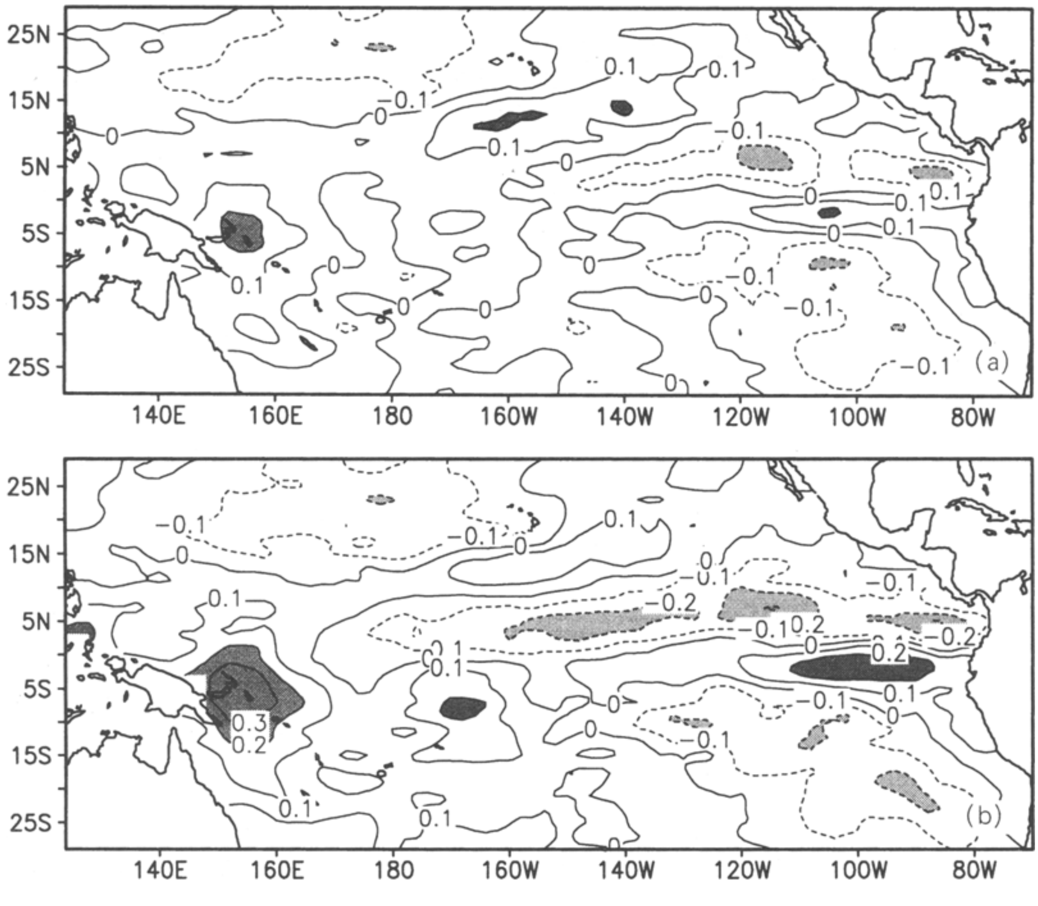
Fig. 1. The time evolution of the monthly NINO3 SSTA (1961–1989).

meridional wind stress anomalies appear in the eastern equatorial Pacific. And with the reduction of the leading time, the anomalous convergence of the meridional wind stress intensifies significantly and expands westward. It is indicated that there may be an inherent relation between the El Niño occurring and the anomalies convergence of meridional wind stress which precedingly appears in the eastern equatorial Pacific. In the next section, in order to study further the relationship between meridional wind stress anomalies and SSTA in the tropical Pacific, we analyze the coupling patterns of them by SVD method.

4. Coupling patterns of SSTA and meridional wind stress anomalies

In the above section we have seen that the leading meridional wind stress in the equatorial eastern Pacific is significantly correlated with the NINO3 SSTA. Similar to the above section, by using SVD method, in this section we analyze the coupling patterns of the tropical Pacific SSTA with the preceding meridional wind stress anomalies by SVD method.

Figure 3 shows the coupling patterns of SSTA and the meridional wind stress anomalies prior to SSTA by six months for the first mode with the largest singular value in SVD. The evolutions of the time coefficients of the first mode are also shown in Fig. 3. Since the first mode has the largest covariance contribution and corresponds to the interannual variation associated with El Niño events, in the following we discuss only this mode.



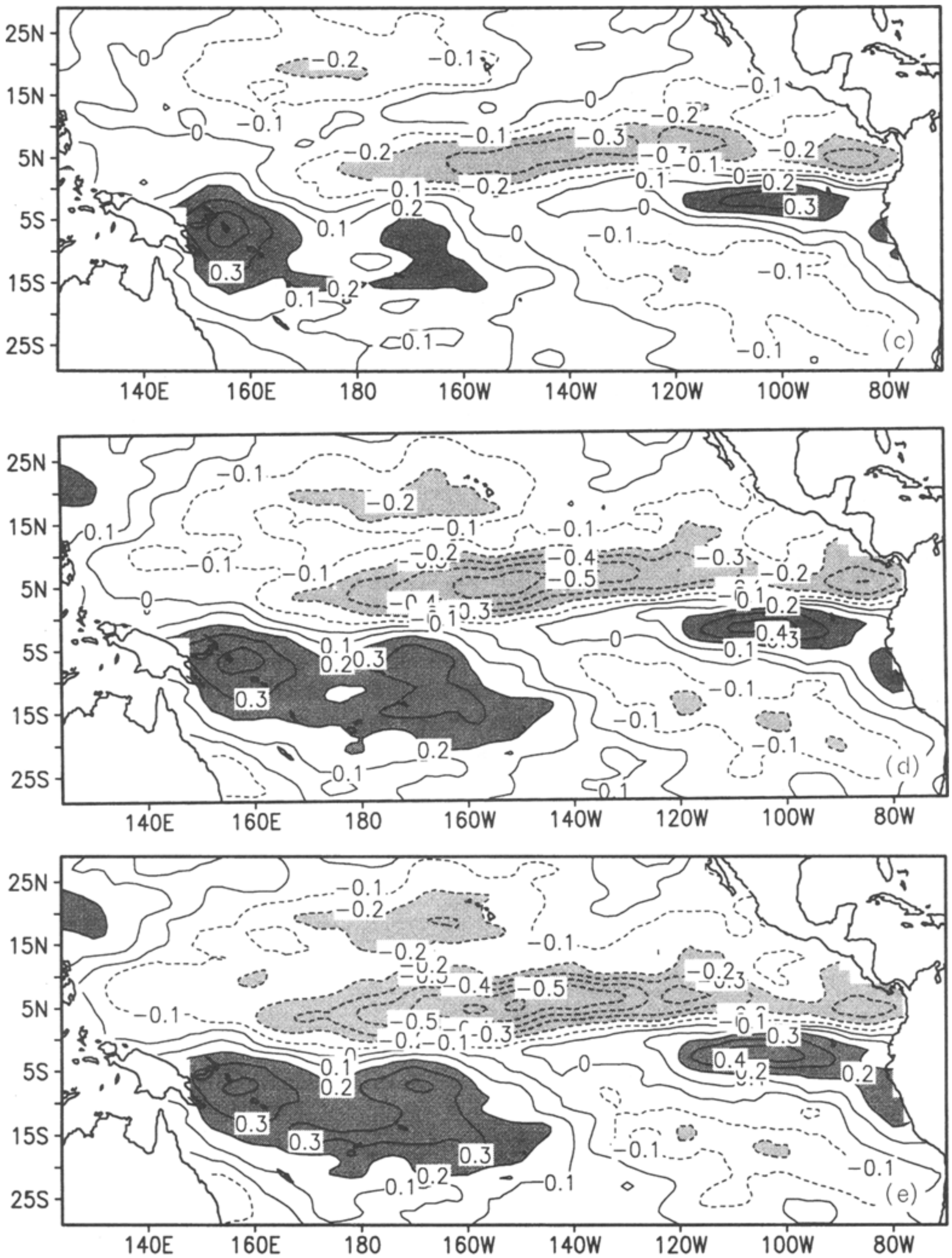


Fig. 2. Correlation coefficients between the NINO3 SSTA and the meridional wind stress prior to NINO3 SSTA by seven months (a), five months (b), three months (c) and one month (d) as well as at the same time (e), respectively. Shadings are the areas with statistical significance at 95% level.

The coupling pattern of meridional wind stress anomalies is given in Fig. 3a. It can be found that Fig. 3a is similar to the correlation pattern in the previous section. There are also anomalous converging of the meridional wind stress near the equator in the eastern equatorial

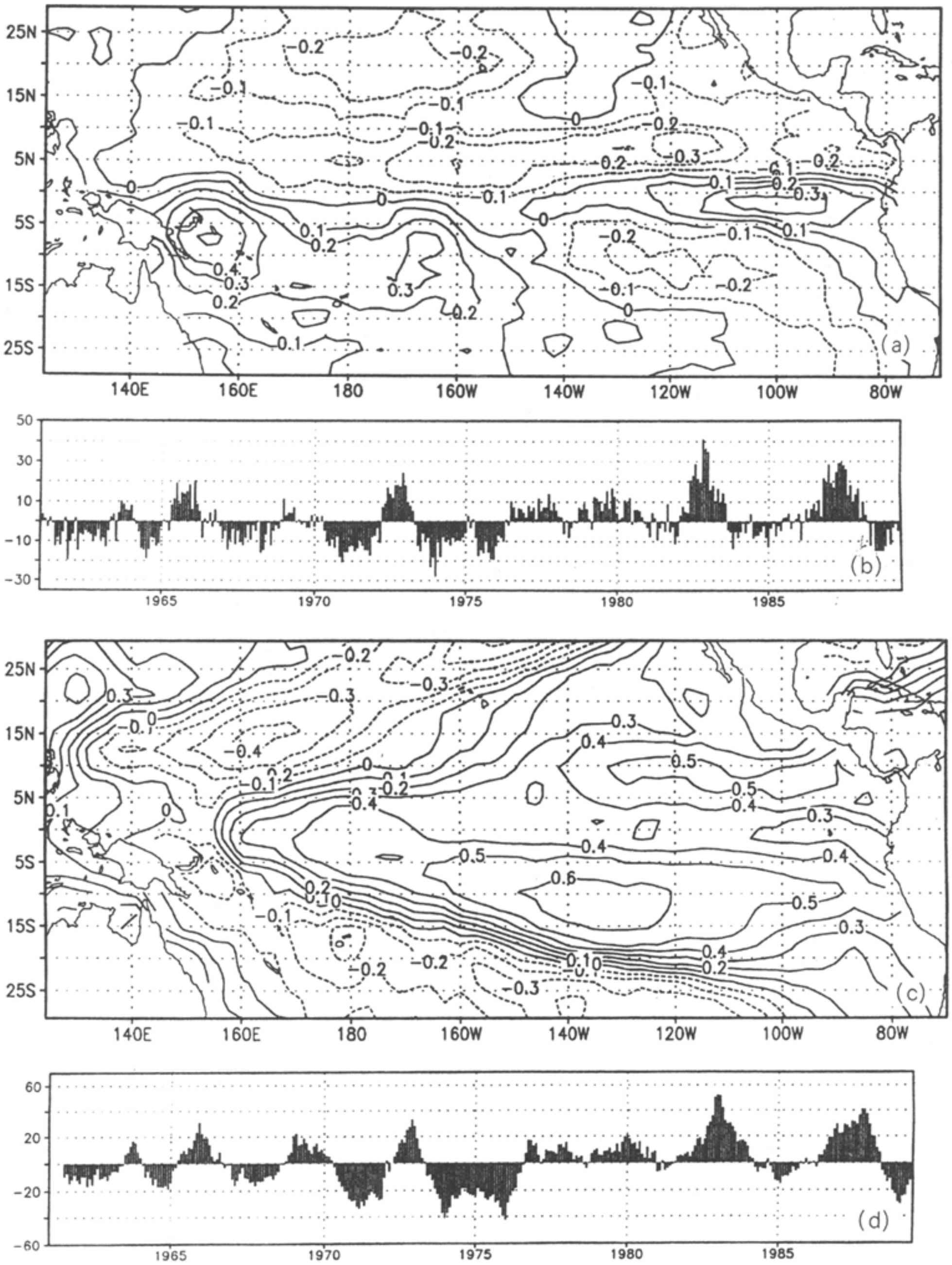


Fig. 3. Coupling patterns of SSTA (c) and the meridional wind stress anomalies prior to SSTA by six months (a) for the first mode with the largest singular value, and evolutions of the time coefficients of coupling patterns of SSTA (d) and meridional wind stress anomalies (b).

Pacific. Moreover, there appears another converging area in the central and western equatorial Pacific. The strongest wind stress anomalies appear in the eastern equatorial Pacific between 120°E and 80°E. The maximum center of northerly wind stress anomalies appears in the north of equator and southerly wind stress anomalies in the south of equator. It is indicated that the strongest anomalous convergence of the meridional wind stress anomalies is in the eastern equatorial Pacific.

The coupling pattern of SSTA is shown in Fig. 3c. Corresponding to the anomalous convergence of the meridional wind stress as shown in Fig. 3a, the positive SSTA appears in the central and eastern tropical Pacific. In addition, it can be seen that although the positive SSTA exists near the equator, centers of the largest SSTA are not at the equator. They are located in the eastern Pacific at about 10°N and 13°S, respectively. It is suggested that the positive SSTA not only near the equator, but also at these places are related to the pattern of the meridional wind stress anomalies as shown in Fig. 3a. The evolutions of time coefficients of coupling patterns of the meridional wind stress anomalies and SSTA for the first mode are shown in Fig. 3b and Fig. 3d, respectively. We can see that they have very similar variations and are of high correlation. Compared with the evolution of the NINO3 SSTA in Fig. 1, their positive peaks correspond well to El Niño events. It is demonstrated that the first mode of the coupling patterns reflects the relations and the features of the interannual variations of the meridional wind stress anomalies and SSTA associated with El Niño events.

Figures 4 and 5 show the coupling patterns of SSTA and the meridional wind stress anomalies prior to SSTA by three months and one month, respectively. Their first modes have the largest singular values in SVD. Similar to the coupling patterns of the meridional wind stress anomalies prior to SSTA by six months (Fig. 3), these first modes of the coupling patterns have the highest correlation coefficients and covariance contributions, and correspond to the interannual variations associated with El Niño events.

From Fig. 4 and Fig. 5, we can see that the distributions of the coupling patterns of SSTA and the meridional wind stress anomalies are quite similar to those for the meridional wind stress anomalies prior to SSTA by six months as shown in Fig. 3. There is no essential difference among the patterns of meridional wind stress anomalies except the changes of their values. As the leading time decreases, both the anomalous northerlies to the north of equator and anomalous southerlies to the south of equator strengthen. The convergence of the meridional wind stress anomalies about the equator becomes stronger. For the coupling patterns of the SSTA, in the central and eastern equatorial Pacific the SSTA becomes higher as the leading time decreases. The positive centers of the SSTA appearing in both sides of equator at about 10°N and 13°S (Fig. 3c) move to 7°N and 10°S at leading time three months (Fig. 4c), and 5°N and 7°S at leading time one month (Fig. 5c). It is suggested the strengthening of the meridional wind convergence about equator is favorable for the SST increasing near equator. In fact, when the wind stress is one month prior to SSTA (Fig. 5), the positive center of SSTA appears in the central and eastern equatorial Pacific, which is similar to the SSTA distribution of an El Niño event.

In the previous section, we have seen that the NINO3 SSTA is significantly correlated with the leading meridional wind stress anomalies in a converging form about the equator and the correlation coefficients get greater as the leading time decreases. Here we can see changes of the coupling patterns of the strengthening of the converging wind stress anomalies about the equator and increasing of SSTA in the equatorial eastern Pacific as the leading time becomes smaller. The evolutions of the time coefficients of the coupling patterns of meridional wind stress anomalies at the leading times of three months and one month are shown in Fig. 4b and Fig. 5b, respectively. Figure 4d and 5d show the time coefficients of the corresponding SSTA, respectively. Compared with Fig. 1, it can be seen that for each El Niño

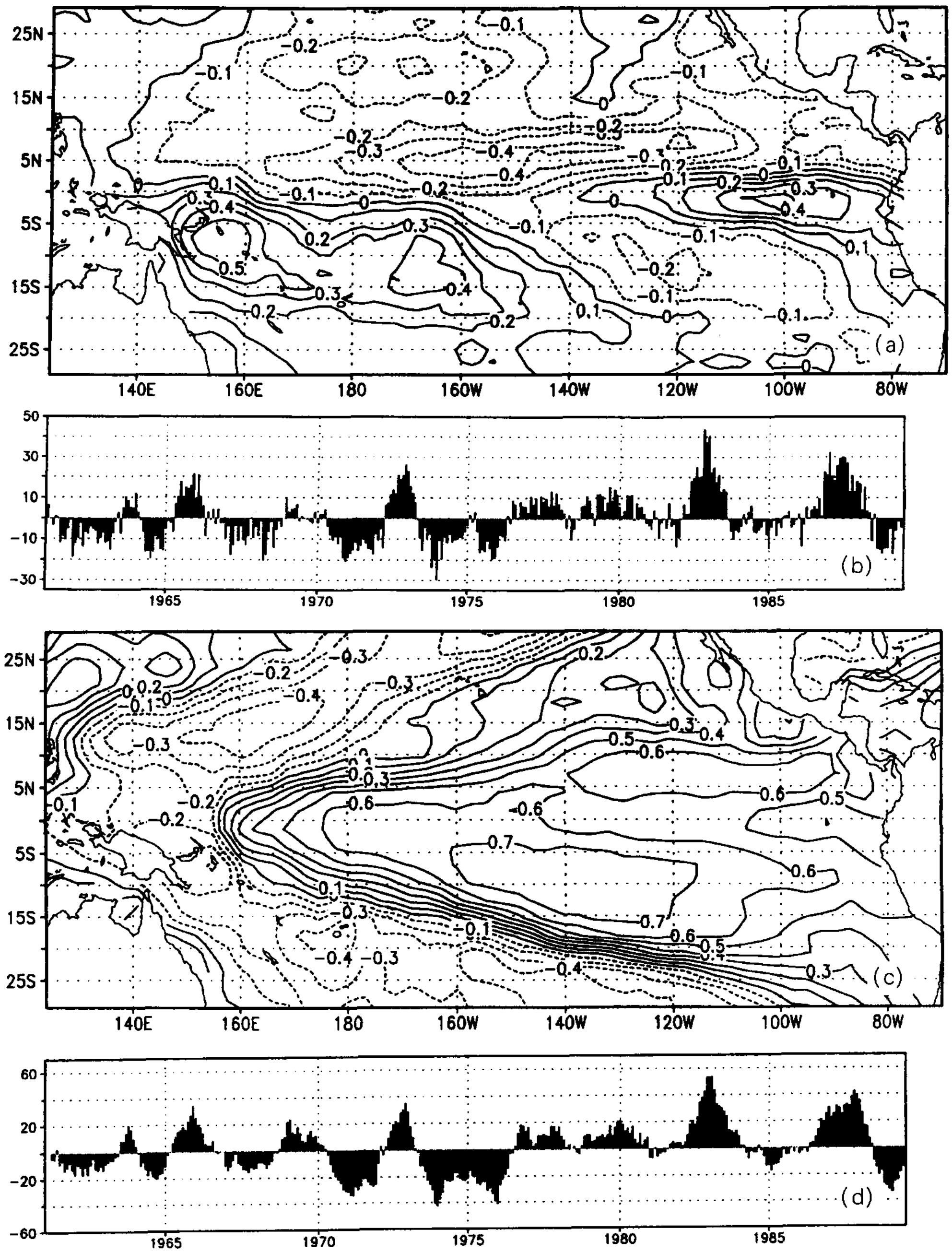


Fig. 4. Same as Fig. 3 but for the meridional wind stress anomalies prior to SSTA by three months.

event there exists a maximum of the time coefficients. Therefore, same as the coupling patterns of wind stress prior to SSTA by six months (see Fig. 3), the coupling patterns given in Figs. 4 and 5 represent the coupling features of leading meridional wind stress anomalies and SSTA in their interannual variations associated with El Niño events.

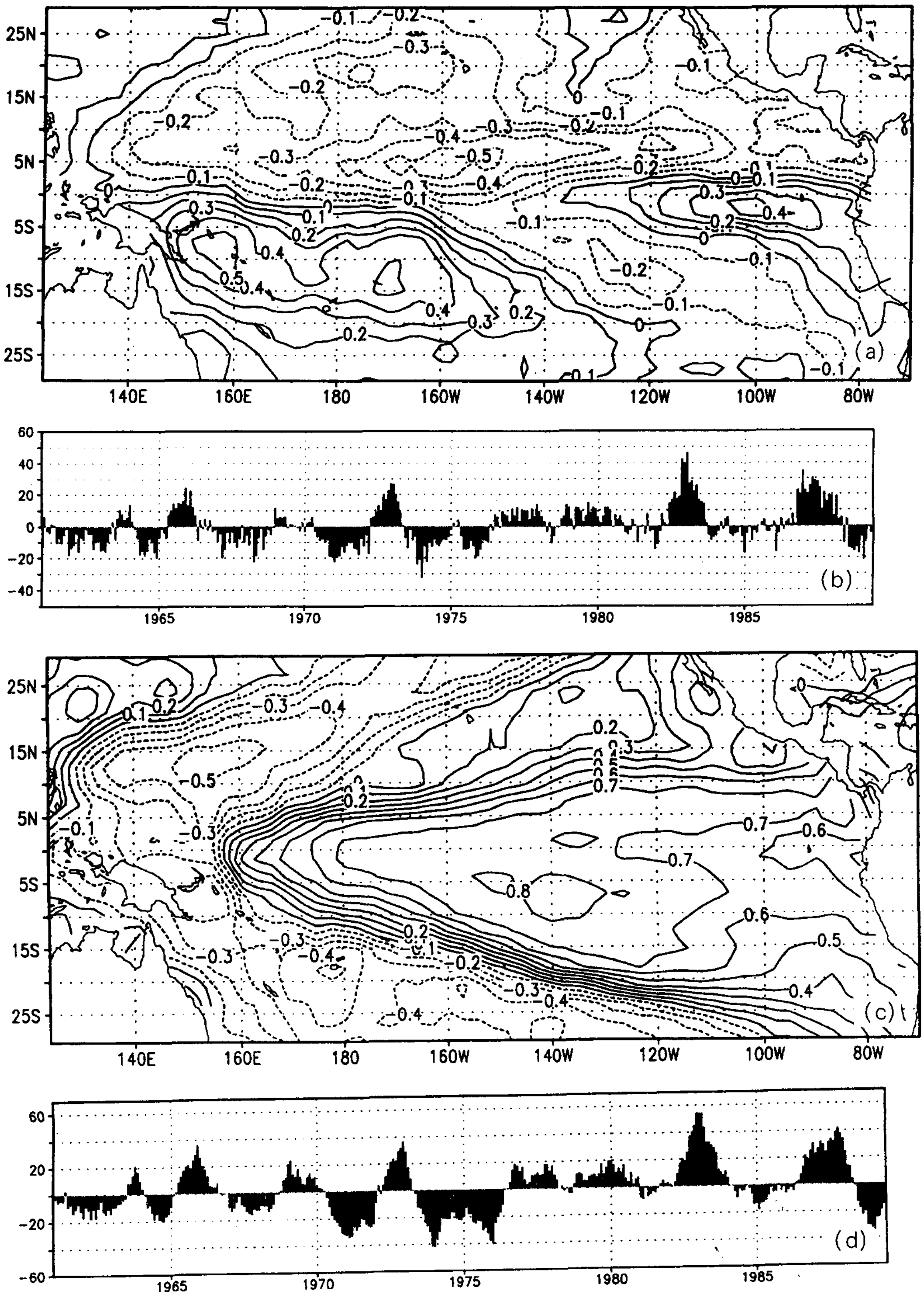


Fig. 5. Same as Fig. 3 but for the meridional wind stress anomalies prior to SSTA by one month.

Table 1 shows the covariance contributions, correlation coefficients and the variance contributions of meridional wind stress anomalies and SSTA for the first mode of the coupling patterns in SVD for the meridional wind stress anomalies prior to SSTA by six months, three months and one month, respectively. From Table 1 it can be seen that with the decreasing of the leading time, the correlations between SSTA and the preceding meridional wind stress anomalies become stronger, and the covariance contributions become larger. The variance contributions of the meridional wind stress anomalies and SSTA are also getting larger as the leading time decreases. The increasing of the covariance contributions and the variance contributions for each field indicates that the first modes of the coupling patterns contribute and explain more and more the real fields as the leading time decreases. And also the smaller the leading time, the more effect of the leading meridional wind stress anomalies in the formation of converging about the equator on the increasing of the positive SSTA in the eastern equatorial Pacific.

Table 1. Parameters of the first mode of the coupling patterns in SVD

Leading months	Covariance contribution	Correlation Coefficient	Variance contri-bution of SSTA	Variance contribution of wind stress anomalies
6	59.90%	0.64	25.52%	5.75%
3	72.15%	0.77	28.16%	6.58%
1	72.57%	0.84	28.43%	7.17%

5. Comparison of the role of zonal and meridional wind stresses in El Niño occurring

As mentioned in the introduction, many researches have pointed out the importance of westerly anomalies over the tropical western Pacific to the occurrence of the El Niño events. In our present analysis, it also shows that the meridional wind stress anomalies may have a significant effect on the warming in the eastern equatorial Pacific. Prior to the warming of the NINO3 SSTA, northerly anomalies to the north of equator and southerly anomalies to the south of equator appear in the eastern equatorial Pacific. In order to compare the role of such convergence in the El Niño occurrence with that of the zonal wind stress, we make the difference between meridional wind stress anomalies averaged over the area 120°–86°W, 3°–9°N and those over the area 120°–86°W, 5°S–1°N. The difference is called V_{str}, which is taken to be an index of the anomalous convergence of meridional wind stress anomalies in the equatorial eastern Pacific. We also make the zonal wind stress anomalies averaged over the area 124°–160°E, 10°S–10°N, called U_{str}, as the index of the zonal wind stress anomalies over tropical western Pacific. The correlation coefficients of the NINO3 SSTA with the leading V_{str} and U_{str} are shown in Fig. 6.

From Fig. 6 we can see that the leading zonal wind stress anomalies in the western tropical Pacific (U_{str}) are positively correlated with the NINO3 SSTA. It means that prior to the increasing of the NINO3 SSTA, westerly anomalies appear in the tropical western Pacific. The correlation is statistically significant from the leading time two to nine months. The largest correlation appears at the leading time four months and the correlation coefficient is 0.33. For the convergence of the leading meridional wind stress anomalies in the eastern equatorial Pacific (V_{str}), there appears negative correlation. It indicates the leading anomalous convergence corresponds to the increasing of the NINO3 SSTA. The correlation increases as the leading time decreases. From the leading time seven months, the correlation becomes

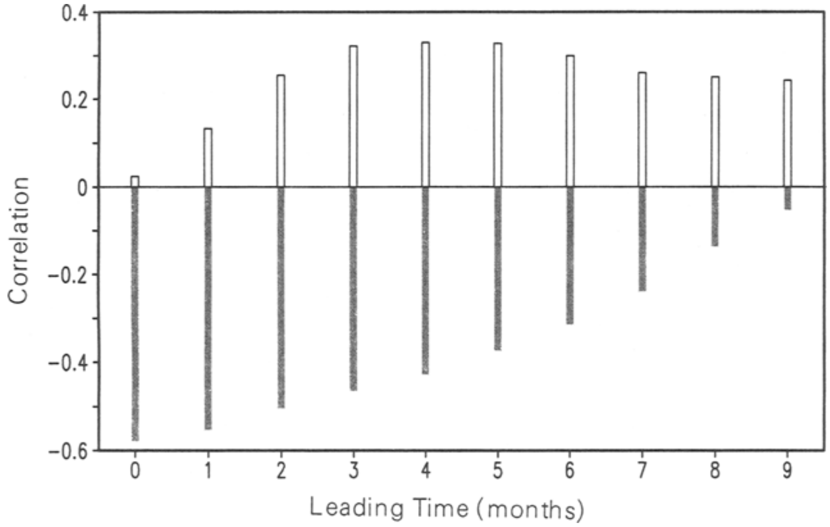


Fig. 6. Correlation coefficients of NINO3 SSTA with leading zonal wind stress anomalies averaged over the area 124°–160°E, 10°S–10°N (outline bar) and with the difference between leading meridional wind stress anomalies averaged over the area 120°–86°W, 3°–9°N and those averaged over the area 120°–86°W, 5°S–1°N (filled bar).

statistically significant. Figure 6 also shows that from the leading time six months, the correlation coefficients for the convergence anomalies in the eastern equatorial Pacific are larger than those for the zonal anomalies in the tropical western Pacific. Compared to the leading zonal wind stress anomalies in the tropical western Pacific, it seems that the increasing of the NINO3 SSTA is more related to the convergence of the leading meridional wind stress anomalies in the eastern equatorial Pacific.

6. Summary and concluding remarks

The analyses in the present paper show that NINO3 SSTA are significantly stically correlated with the preceding meridional wind stress anomalies in a converging form about the equator in the eastern equatorial Pacific. Prior to the rising of the SST in the NINO3 region by more than half a year, there exists the correlation of NINO3 SSTA with the northerly wind stress anomalies to the north of the equator and southerly anomalies to the south of equator in the equatorial eastern Pacific. Such convergence of the meridional wind stress anomalies intensifies and expands westward as the leading time reduces. Compared to the leading zonal wind stress anomalies in the tropical western Pacific, it seems that the increasing of the NINO3 SSTA is more related to the convergence of the leading meridional wind stress anomalies in the eastern equatorial Pacific.

The coupling patterns between SSTA and the leading meridional wind stress anomalies for the first mode with the largest singular value in SVD have similar features to that of the correlation analyses. The coupling pattern of SSTA shows that while the positive SSTA in the central and eastern equatorial Pacific, the leading meridional wind stress anomalies are in the form of northerly wind stress anomalies to the north of equator and southerly wind stress anomalies to the south of equator, which converge about the equator. As the leading time reduces, the preceding anomalous convergence becomes stronger and the SSTA in the central and eastern equatorial Pacific become higher, and the SSTA distribution is getting similar to that of an El Niño event. The evolutions of time coefficients of the coupling patterns have the maximum peaks during each El Niño episode. It is indicated that the coupling patterns of SSTA and the leading meridional wind stress anomalies for the first mode with the largest singular value in SVD correspond to their interannual variations associated with El Niño events.

The analyses demonstrate that the leading meridional wind stress anomalies in the central and eastern equatorial Pacific are significantly correlated with the occurrence of El Niño events. In order to understand the physical relation of the converging wind stress to the onset of El Niño, in the next part of this study, based on the observational facts revealed here, an ideal convergent meridional wind stress anomaly will be constructed. By using a simple tropical oceanic model, theoretical analyses will be given to investigate the response of the tropical ocean to the convergent meridional wind stress and the dynamical role of the convergent wind stress in the occurrence of the El Niño event.

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热带太平洋经向风应力异常与 El Niño 的发生
——(I) 资料诊断

张人禾　　赵　刚　　谭言科

摘　要

对热带太平洋海表经向风应力异常与 El Niño 事件之间的关系进行了诊断分析。结果表明，超前的经向风应力距平场与 NINO3 区(150°–90°W, 5°S–5°N)的海面温度异常(SSTA)有显著的超前相关，这种相关性在超前 6 个月甚至更早一些就有显示。利用奇异值分解方法分析超前的经向风应力距平场与太平洋海表温度异常场之间的耦合模，结果表明对应于赤道中东太平洋的海面温度异常升高，大气风应力场在超前 6 个月甚至更早的时候，在赤道中东太平洋表现为辐合的经向异常风应力场，即赤道以北为北风异常应力，赤道以南为南风异常应力。这种耦合模的时间系数与 NINO3 SSTA 指数所表示的 El Niño 事件有很好的对应关系，表明这种耦合模反映的正是超前的经向风应力异常与 El Niño 事件所对应的海表温度异常之间的相关模态。通过与热带西太平洋纬向风应力异常的比较，赤道中东太平洋辐合的经向风应力异常与 El Niño 事件发生的同样具有重要的联系。

关键词: 经向风应力，厄尔尼诺(El Niño)