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ENSO Cycle Associated with the Tropospheric Zonal Wind Anomalies over the Global Region

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Abstract

In our previous paper, an analysis of the El Niño/Southern Oscillation (ENSO) cycle associated with the vertically-integrated equatorial tropospheric (1000-100hPa) zonal wind anomalies in different regions over the Pacific Basin was made. The data sets used are the monthly US National Center of Environmental Prediction (NCEP) reanalysis wind and the monthly sea surface temperature from 1950 to 1998. Some relationships of the El Niño/Southern Oscillation cycle associated with the zonal wind anomalies at the western, central and eastern equatorial Pacific Basin have been revealed. To examine the relationship of El Niño/Southern Oscillation cycle associated with the widespread spatial zonal wind anomalies, the global zonal wind anomalies have been analysed in the present paper. A fact that has been identified is the meridional migration of zonal wind anomalies starting from the equator in the inter-annual time-scale not only for the global region but also for the whole Pacific Basin. The wavelet analysis of both zonal wind anomalies along the various latitudes and sea surface temperature anomalies (SSTA) in the equatorial eastern Pacific (EEP) shows that there are different phase-lag relationships related to our previous study. Along the equatorial zone and the equatorial Pacific, the phase of zonal wind anomalies in most events is earlier than that of equatorial eastern Pacific sea surface temperature anomalies (or El Niño event) for about 5-13 months at the inter-annual time-scale. Along the subtropical zones, the same variation in phase between zonal wind anomalies and equatorial eastern Pacific sea surface temperature anomalies are observed in the inter-annual time-scale for many cases. According to these observations, a scenario of planetary-scale sea-air interaction, different from the previous study of the regional sea-air interaction, has been distinguished.

Key words: Global region, Pacific Basin, wavelet analysis, zonal wind, El Niño/Southern Oscillation

1. Introduction

In our previous paper (*Qian et al.*, 2000), an analysis of the El Niño/Southern Oscillation (ENSO) cycle associated with the vertically-integrated equatorial tropospheric (1000-100hPa) zonal wind anomalies in different regions over the Pacific Basin was made. The data sets used are the monthly US National Center of Environmental Prediction (NCEP) reanalysis wind and the NCEP monthly sea surface temperature from 1950 to 1998. Some relationships of El Niño/Southern Oscillation cycle associated with the zonal wind anomalies at the western, central and eastern equatorial Pacific Basin have been revealed. In the equatorial western Pacific, the phase

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of zonal wind anomalies in most events is earlier than that of equatorial eastern Pacific sea surface temperature anomaly (or El Niño event) for about 7-13 months. In the equatorial central Pacific, there is little phase-relationship between them. In the equatorial eastern Pacific, the phase of equatorial eastern Pacific sea surface temperature anomaly is mostly earlier than that of zonal wind anomalies for about 4-9 months. The relationships are explained using a simple tropical sea-air coupled model (*Gill*, 1980), which includes a positive/negative feedback scenario that seems to hold during the El Niño/Southern Oscillation cycle. Also, decade-scale active and break periods of the tropical sea-air interaction are described. According to these findings, we have predicted that a strong El Niño is expected in 2001-2002.

These results only reveal the relationships of equatorial eastern Pacific sea surface temperature anomalies associated with the regional zonal wind anomalies over the equatorial Pacific. The relationship between the El Niño/Southern Oscillation cycle and the zonal wind anomalies over the whole equatorial Pacific as well as the global atmosphere is still unknown. In the present paper, we still pay attention to the tropospheric (1000-100hPa) temporal zonal wind anomalies and extend them to the global latitudes and the Pacific Basin latitudes. The data sets used are still the monthly NCEP/NCAR reanalysis wind (*Kalnay et al.*, 1996) and the monthly NCEP/NCAR sea surface temperature from 1950 to 1999. The methods used are composite analysis, wavelet analysis and correlation analysis for different time lags.

Because the data used and the calculation method were described in our previous work (*Qian et al.*, 2000), we will directly introduce some new results. The meridional migration of zonal wind anomalies starting from the equator for the global zonal wind anomalies and the Pacific Basin zonal wind anomalies is described in Section 2. The observed facts of the zonal wind anomalies along various latitudes over the global region and the Pacific Basin region associated with the equatorial eastern Pacific sea surface temperature anomalies are shown from Sections 3 to 4. Wavelet transform for sea surface temperature anomalies and zonal wind anomalies in different regions is performed, and the cross-lag/lead correlation analysis is illustrated in Section 5. Sea-air interaction of multiple time-scale scales is addressed in Section 6. Finally, the conclusion and discussion are given in Section 7.

2. Meridional migration of zonal wind anomalies

The data sets used are the monthly-reanalysed winds of the NCEP/NCAR from January 1950 to December 1999 with a horizontal resolution of 2.5 degrees. The zonal wind anomalies along different latitude zones from 75N to 75S are first calculated. Band of 75N-75S was divided into 21 latitude zones with an interval of 7.5 degrees. The zonal wind anomalies along each zone from 1000hPa to 100hPa (total 12 levels) is calculated using the following formula.

$$ZWA = \frac{1}{\Delta\varphi \cdot \Delta p} \int_p \int_\varphi [u] d\varphi dp \tag{1}$$

where, [u] defines the regional zonal wind anomaly, $\Delta\varphi$=7.5, and p the pressure from 100 to 1000hPa, Δp=900hPa. Totally 600-month zonal wind anomalies time series at different longitudes are calculated relative to the climatological mean of 1950-1999. Finally, a monthly value of zonal wind anomalies averaged over an individual latitude zone is calculated from 75N to 75S. Figure 1a shows the monthly zonal wind anomalies as a cross-section diagram between time (1950-1999) and the 45N to 45S latitude zones. The solid-line areas with the grey scale indicate the westerly anomalies while the dashed-line areas show the easterly anomalies. The bold dashed line indicates the westerly maximum at different latitudes with time. The westerly anomalies most probably appear first over the equatorial zone, then shift pole-wards. A similar situation can be noted in Figure 1b where the monthly zonal wind anomaly section is averaged from an individual zone between 120E and 80W over the Pacific Basin. It was noted that the travelling time of westerly anomalies from the equator to high latitudes is several years. The years of the bold dashed lines crossing the equator correspond to 1951, 1957, 1962, 1968, 1971, 1976, 1979, 1982, 1986-87, 1989-90, 1992, and 1996-97. The zonal wind anomalies and their migrations can be seen as the reflection of the planetary-scale atmospheric circulation anomalies. These anomalies may be linked with the sea surface temperature anomalies. *Bjerkness* (1966) proposed a scenario in which the equatorial westerly anomalies lead to sea surface temperature anomalies arising in the tropical region, after which the positive sea surface temperature anomalies drive westerly anomalies over subtropical latitudes because of the Hadley circulation running faster. Finally the trade wind anomalies over the tropical regions lead to the positive sea surface temperature anomalies returning to normal status. This scenario describes a positive/negative feedback of sea surface temperature anomalies linked with the tropospheric wind anomalies. By using the long-term wind data, we examined the scenario.

3. Zonal wind anomalies along the equatorial zone

The relationship between the zonal wind anomalies along the equatorial zone and the sea surface temperature anomalies in the equatorial eastern Pacific were primarily studied. Based on the time series of NINO3 region (5N-5S, 150W-90W) sea surface temperature anomalies, the El Niño event is defined as the sea surface temperature anomalies reaching 0.5^{o}C and persisting for at least three consecutive months. Under this definition, from 1950 to 1998 thirteen cases of warming processes, or El Niño events, appearing in 1951-52, 1953, 1957-58, 1963-64, 1965-66, 1968-69, 1972-73, 1976-77, 1979, 1982-83, 1986-87, 1991-92 and 1997-98, were determined in our previous work (*Qian et al.*, 2000). The strongest process appeared in 1997-98 and the weakest one in 1979. Another two short-lived processes took place in early 1993 and late 1994. Those events reflect the oceanic signals that will be used to compare with the atmospheric circulation anomalies.

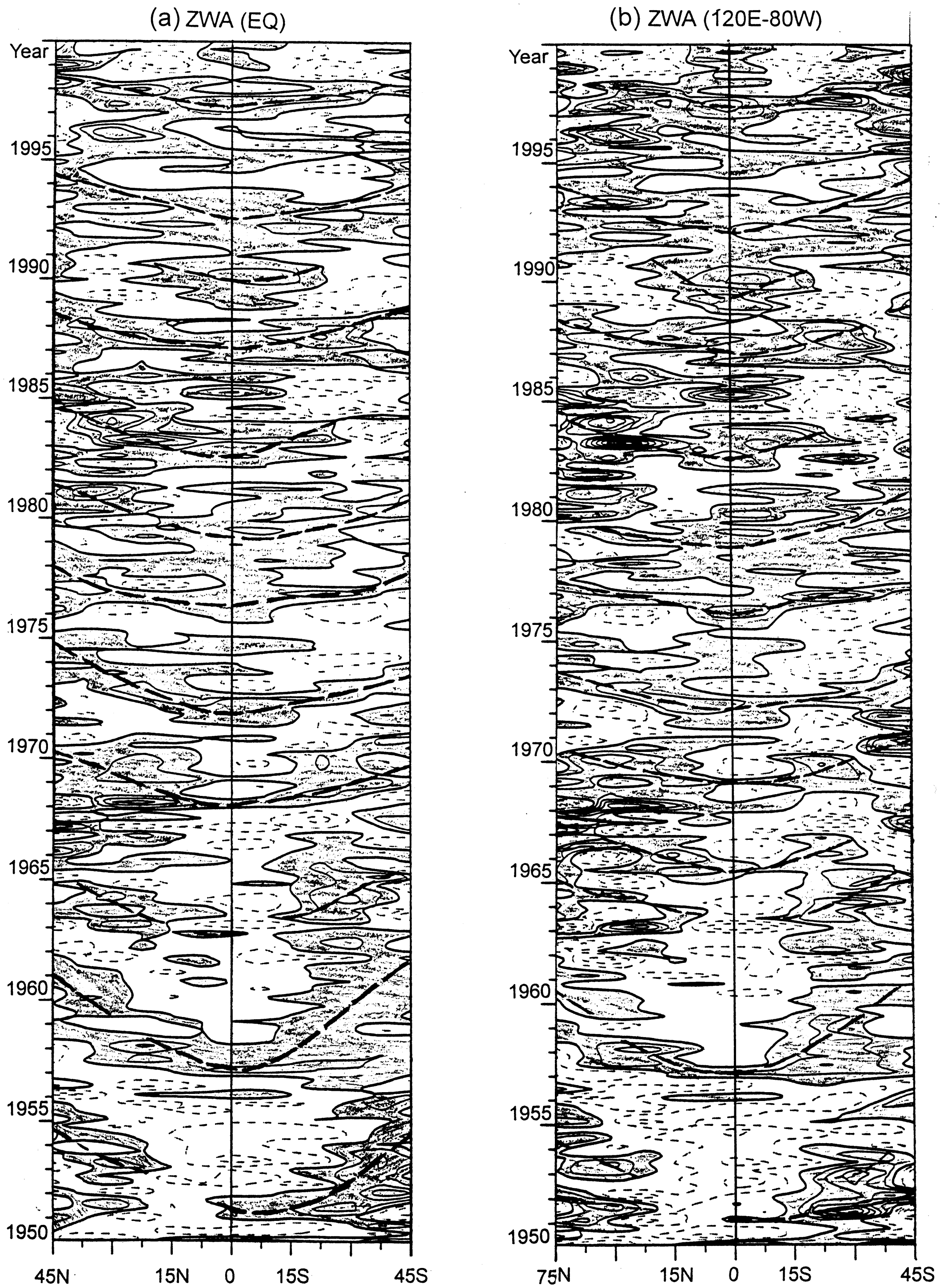

Fig. 1. Tropospheric (1000-100hPa) vertically-integrated zonal westerly wind anomalies (solid-line with grey-scale areas) and easterly wind anomalies (dashed-line areas) related to climatological mean (1950-1999) along different latitudes for (a) globe and (b) the Pacific Basin (120E-80W) from 45N to 45S (interval: 1 m/s). Heavy dashed line indicates the westerly maximum.

Figure 2 shows the zonal wind anomaly time series along the equatorial zone and the monthly NINO3 region sea surface temperature anomaly time series. The dashed line indicates the sea surface temperature anomalies in the NINO3 region and the solid line represents the 5-month-running-mean series of zonal wind anomalies along the equatorial zone (2.5S-2.5N, 0-360). From 1950 to 1998, thirteen warming processes as described above can be found in this figure. Some phase-lag relations can be noted from both the series of sea surface temperature anomalies and zonal wind anomalies. The phase-lag relationships between zonal wind anomalies over the equatorial Pacific (2.5S-2.5N, 120E-80W) and NINO3 region sea surface temperature anomalies can also be seen in Figure 3. The strong El Niño events appear particularly when positive zonal wind anomalies turn to negative ones, such as in 1957-58, 1972-73, 1982-83, and 1997-98.

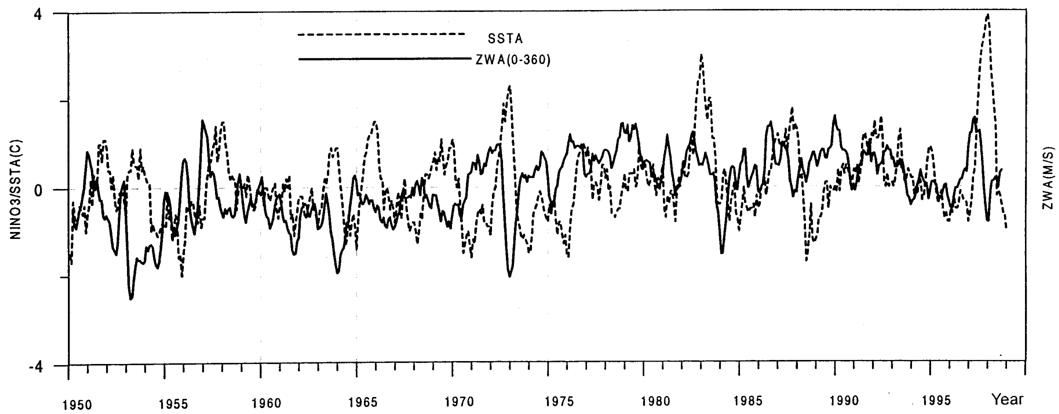

Fig. 2. Monthly NINO3 region sea surface temperature anomalies (^{o}C) and zonal wind anomalies (m/s) time series at the region of the equatorial zone (2.5N-2.5S, 0-360E). Dashed line indicates the sea surface temperature anomalies in the NINO3 region and the solid line represents the 5-month-running-mean series of zonal wind anomalies along the equatorial zone.

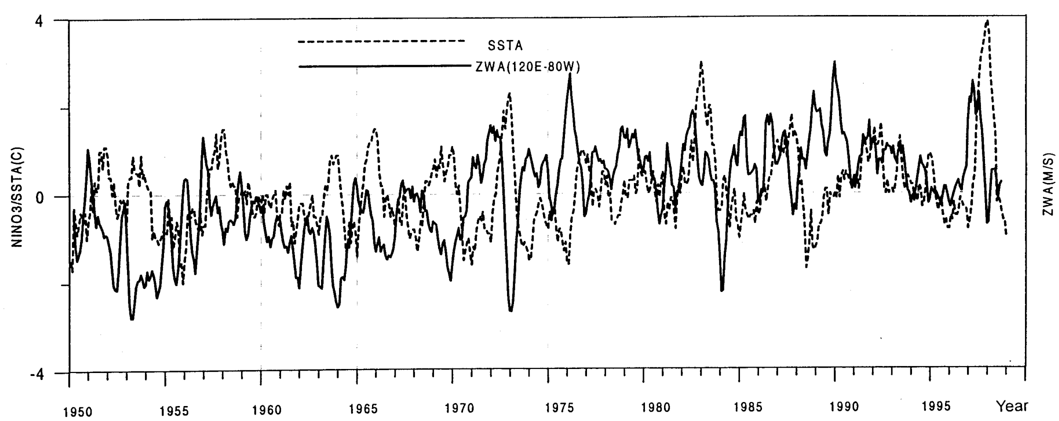

Fig. 3. Same as in Figure 2 but for the zonal wind anomalies at the region of the equatorial Pacific Basin (2.5N-2.5S, 120E-80W).

4. Zonal wind anomalies in the subtropical zones

Figure 4 shows the relationship between El Niño/Southern Oscillation cycle and zonal wind anomalies in the north subtropical zone, by plotting the zonal wind anomalies time series at the region of 0-360E, 27.5N-32.5N and the monthly NINO3 region sea surface temperature anomalies time series. The same variation in phase between zonal wind anomalies and sea surface temperature anomalies can be found for many El Niño processes, such as those occurring in 1956-57, 1965, 1968-69,1972-73, 1976-77, 1986-87, and 1997-98. For some warming events, such as in 1982-83, and 1991-92, the phases of sea surface temperature anomalies were earlier than those of zonal wind anomalies while in the early 1950s the reverse was observed. The similar relationship between zonal wind anomalies over the north subtropical Pacific (120E-80W, 27.5N-32.5N) and NINO3 region sea surface temperature anomalies can also be seen in Figure 5 although the amplitude of zonal wind anomalies in Figure 5 is larger

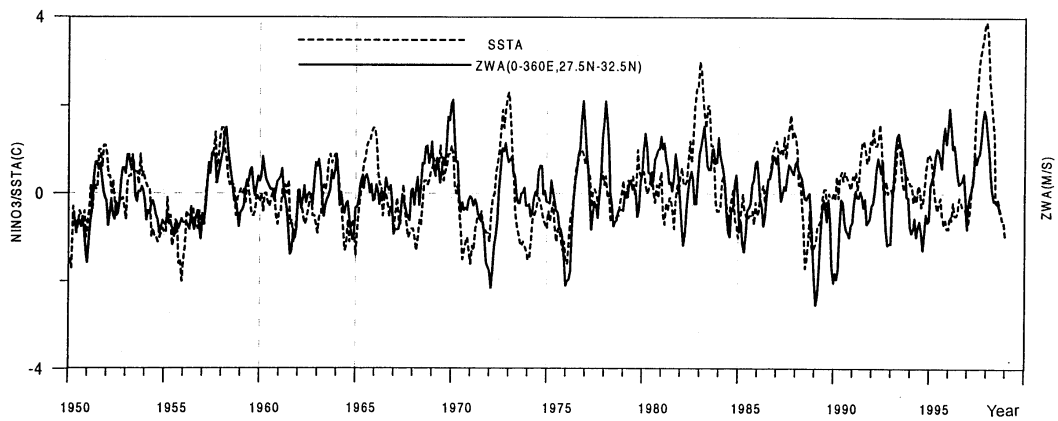

Fig. 4. Same as in Figure 2 but for the zonal wind anomalies at the region of the north subtropical zone (27.5N-32.5N, 0-360E).

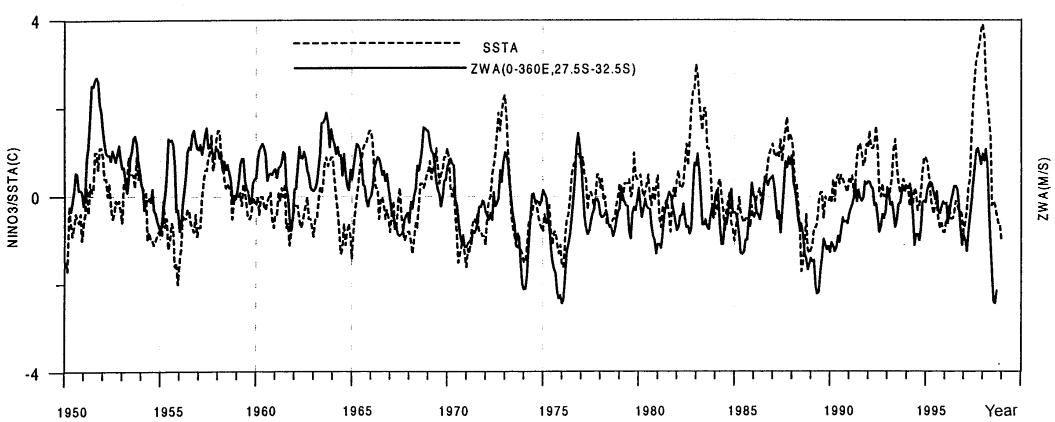

Fig. 5. Same as in Figure 2 but for the zonal wind anomalies at the region of the north subtropical Pacific Basin (27.5N-32.5N, 120E-80W).

than that in Figure 4. In these two figures, a converse relationship between zonal wind anomalies and sea surface temperature anomalies is shown for 1995-96. In many cases the same variation in phase between the zonal wind anomalies and the equatorial eastern Pacific sea surface temperature anomalies can be seen in Figure 4 and Figure 5. Similarly the zonal wind anomalies for the subtropical Southern Hemisphere are plotted in Figure 6 and Figure 7. In Figure 7, the larger amplitude of zonal wind anomalies can be found in the last 49 years if comparing with the amplitude of zonal wind anomalies in Figure 6. We only focus on the phase relationship between zonal wind anomalies and sea surface temperature anomalies in Figure 6 and Figure 7. In Figure 6, some El Niño events such as in 1951-52, 1953, 1963-64, 1972-73, 1976-77, 1986-87, and 1997-98 coincide with the positive zonal wind anomalies in phase. In Figure 7, El Niño events in 1968-69, 1972-73, 1976-77, 1982-83, 1986-87, and 1997-98 as well as the long-term warming process from 1991-1994 are consistent with the positive zonal wind anomalies

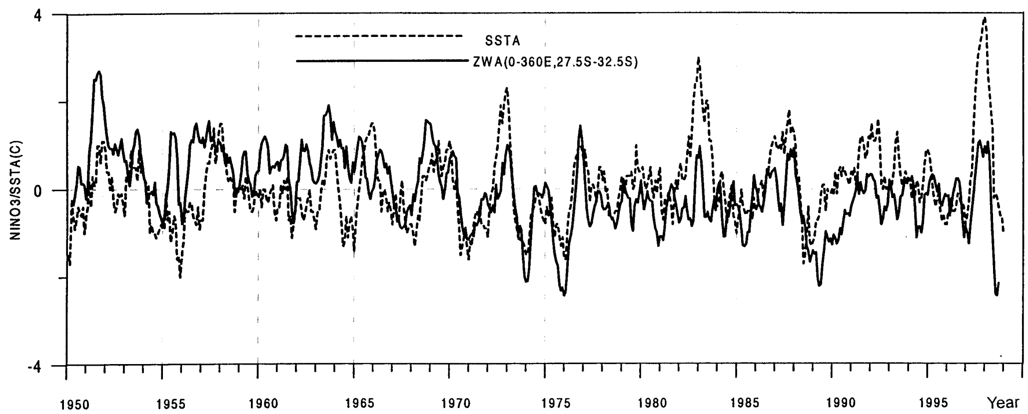

Fig. 6. Same as in Figure 2 but for the zonal wind anomalies at the region of the south subtropical zone (27.5S-32.5S, 0-360E).

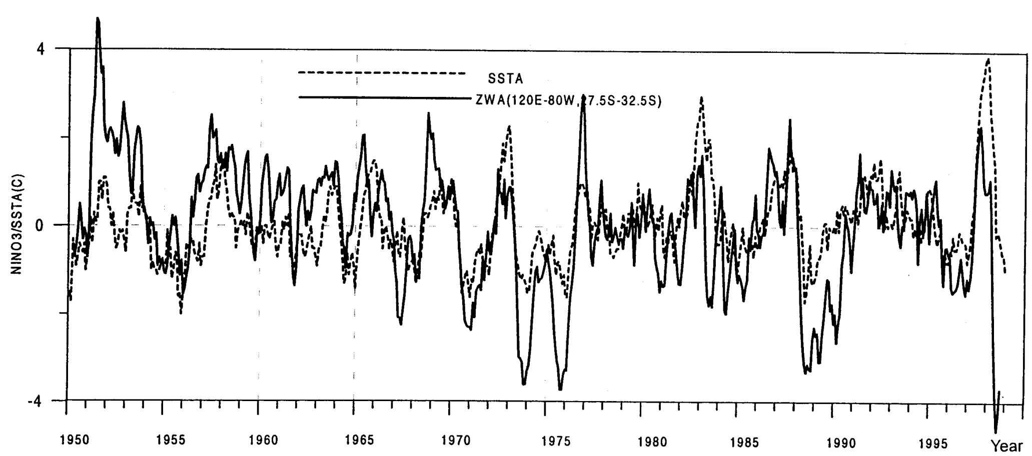

Fig. 7. Same as in Figure 2 but for the zonal wind anomalies at the region of the south subtropical Pacific Basin (27.5S-32.5S, 120E-80W).

in this latitude. It is interesting that in these two figures the same variation in phase between zonal wind anomalies and sea surface temperature anomalies can be noted in the past 49 years for many positive sea surface temperature anomalies and negative sea surface temperature anomaly cases.

5. Correlation analysis

As shown from Figure 2 to Figure 7, there are some statistical relationships between zonal wind anomalies at different regions and sea surface temperature anomalies in the equatorial eastern Pacific. Those relationships may have something to do with the sea-air interactions of multiple time-space scales (*Qian and Wang*, 1997). The wavelet transform method (*Lau and Weng*, 1995) can be performed to extract the inter-annual and inter-decadal time-scale information contained within these two time series. In this paper, the information from inter-annual time-scale for both zonal wind anomalies and sea surface temperature anomalies is our focus. We first calculate the coefficients of wavelet transforms with time-scales ranging from 2 to 150 months for the NINO3 region sea surface temperature anomalies and the zonal wind anomalies in different regions. To determine at which time-scale the phase-relationship holds more consistently, this section will display the results of time-lag correlation between different time-scale components with the time lag from -24 to 24 months based on both series plotted from Figure 2 to Figure 7. Figure 8 shows the cross time-lag correlation, sea surface temperature anomalies and zonal wind anomalies in the equatorial zone as well as the equatorial Pacific. From Figure 8a, the pronounced positive correlation (coefficient as high as 0.6) appears at 60-80 month time-scale with about 9-month leading of zonal wind anomalies to sea surface temperature anomalies. If taking correlation coefficients 0.5 or –0.5 as the threshold of significance for the total of 13 El Niño cycles plotted in Figure 2, the positive zonal wind anomalies over the equatorial zone leads the positive sea surface temperature anomalies in the equatorial eastern Pacific by about 5~13 months ahead at a 70 month time-scale. From 30 to 110 month scales, there is little relationship between zonal wind anomalies and sea surface temperature anomalies with time-lag equalling zero. In the equatorial Pacific, the same relationship is plotted in Figure 8b. As a result, zonal wind anomalies at the equatorial zonal region and the equatorial Pacific can statistically be seen as an early signal for indicating El Niño/Southern Oscillation events at the inter-annual time-scale.

Figure 9 shows the cross time-lag correlation between sea surface temperature anomalies and zonal wind anomalies at the north subtropical zone (0-360, 27.5N-32.5N) and the north subtropical Pacific Basin (120E-80W, 27.5N-32.5N). It is clearly shown that the positive correlation appears from –3 to –6 months at 70-80 month time-scale, which means the positive zonal wind anomalies lag behind the positive sea surface temperature anomalies about 4-5 months. It is also easy to understand from Figure 4 and Figure 5 that there were several cases when the phase of sea surface temperature anomalies led that of zonal wind anomalies for several months. Figure 10 displays the cross time-lag correlation between sea surface temperature anomalies and

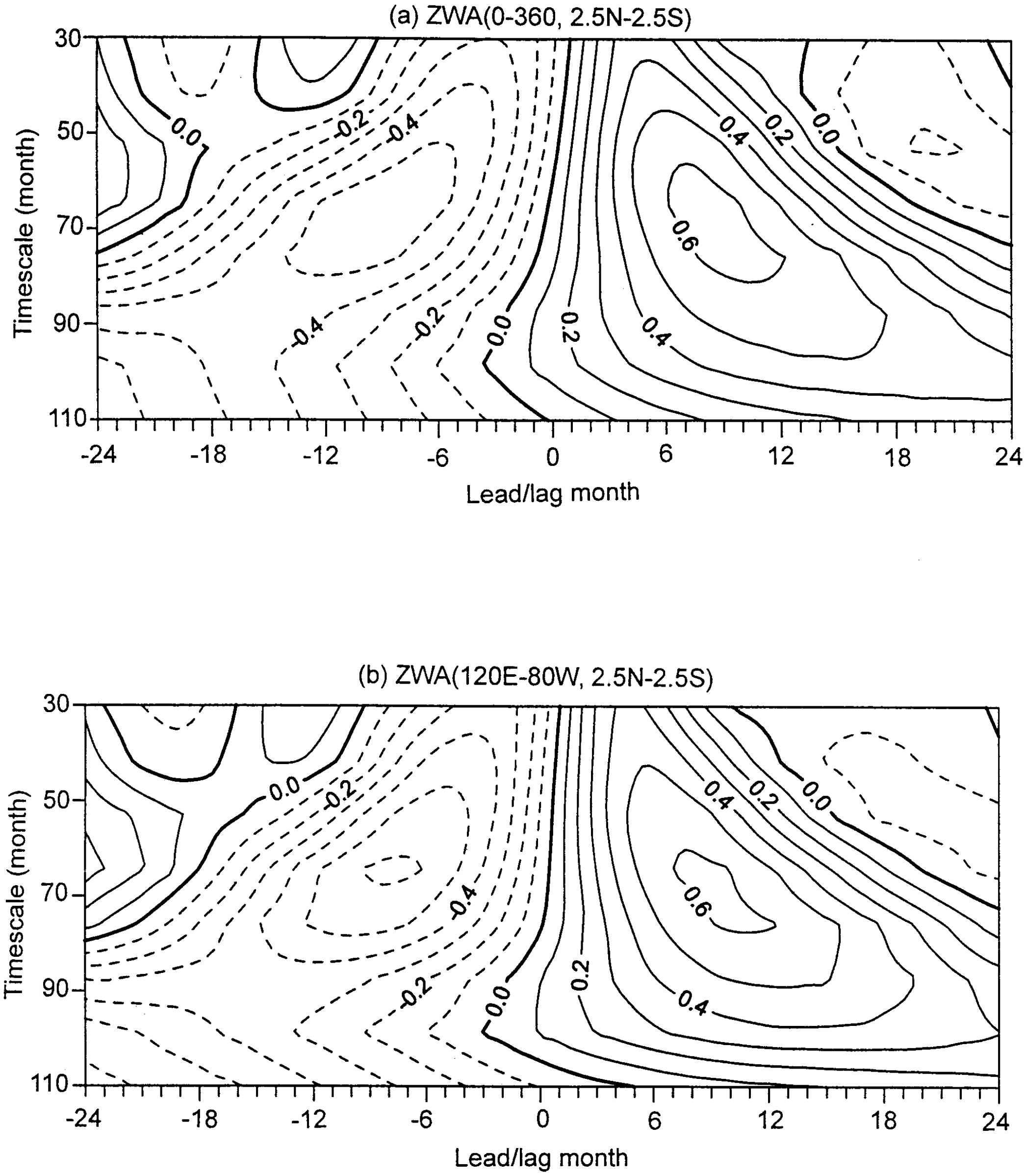

Fig. 8. Time-lag correlation coefficients of NINO3 region sea surface temperature anomalies associated with zonal wind anomalies at regions of (a) the equatorial zone and (b) the equatorial Pacific.

zonal wind anomalies at the south subtropical zone (0-360, 27.5S-32.5S) and the south subtropical Pacific Basin (120E-80W, 27.5S-32.5S). The highest correlation is noted at the zero-lag month. For the zonal wind anomalies at the south subtropical zone, the correlation coefficient is higher than 0.6 at the 70-month time-scale. At the south subtropical Pacific, the correlation coefficient reaches 0.8 at the 70-month time-scale. Both Figure 6 and Figure 7, in many cases, show the same variation in phase between zonal wind anomalies and sea surface temperature anomalies.

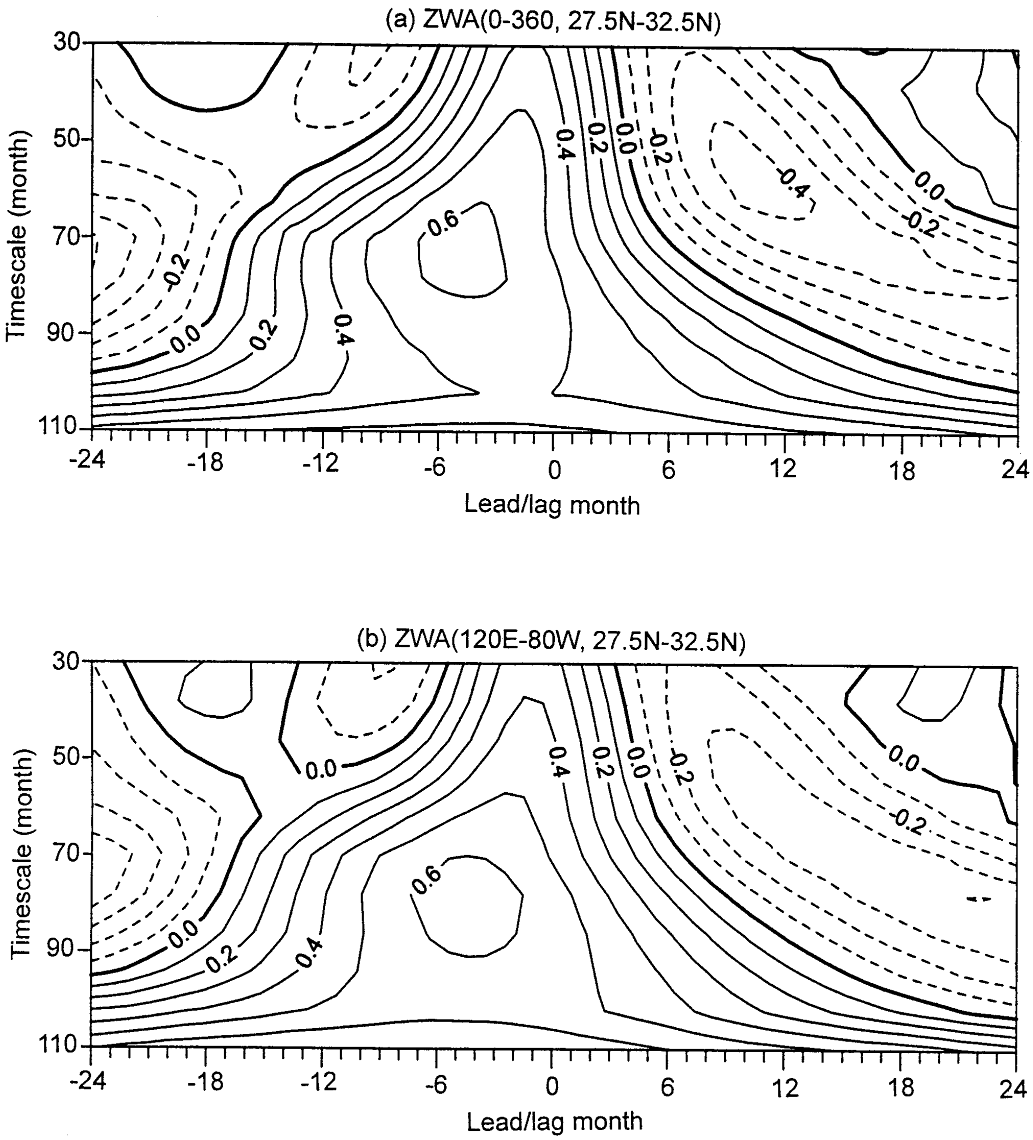

Fig. 9. Same as in Figure 8 but for zonal wind anomalies at regions of (a) the north subtropical zone and (b) the north subtropical Pacific.

From Figure 8 to Figure 10, it was noted that the maximum correlation between zonal wind anomalies and sea surface temperature anomalies appears at about 70-month time-scale. It means that the signal at the 70-month time-scale for both zonal wind anomalies and sea surface temperature anomalies is more important than other time-scales. Therefore, we retain the signals of the 70-month time-scale and filter others. Figure 11 shows the variations of zonal wind anomalies at the 70-month time-scale over the equatorial Pacific, subtropical north and south Pacific relative to NINO3 region sea surface temperature anomalies. From Figure 11, thirteen warming processes can be clearly noted. In Figure 11a, the phase variation of zonal wind anomalies at the equatorial Pacific is generally earlier than that of NINO3 region sea surface temperature

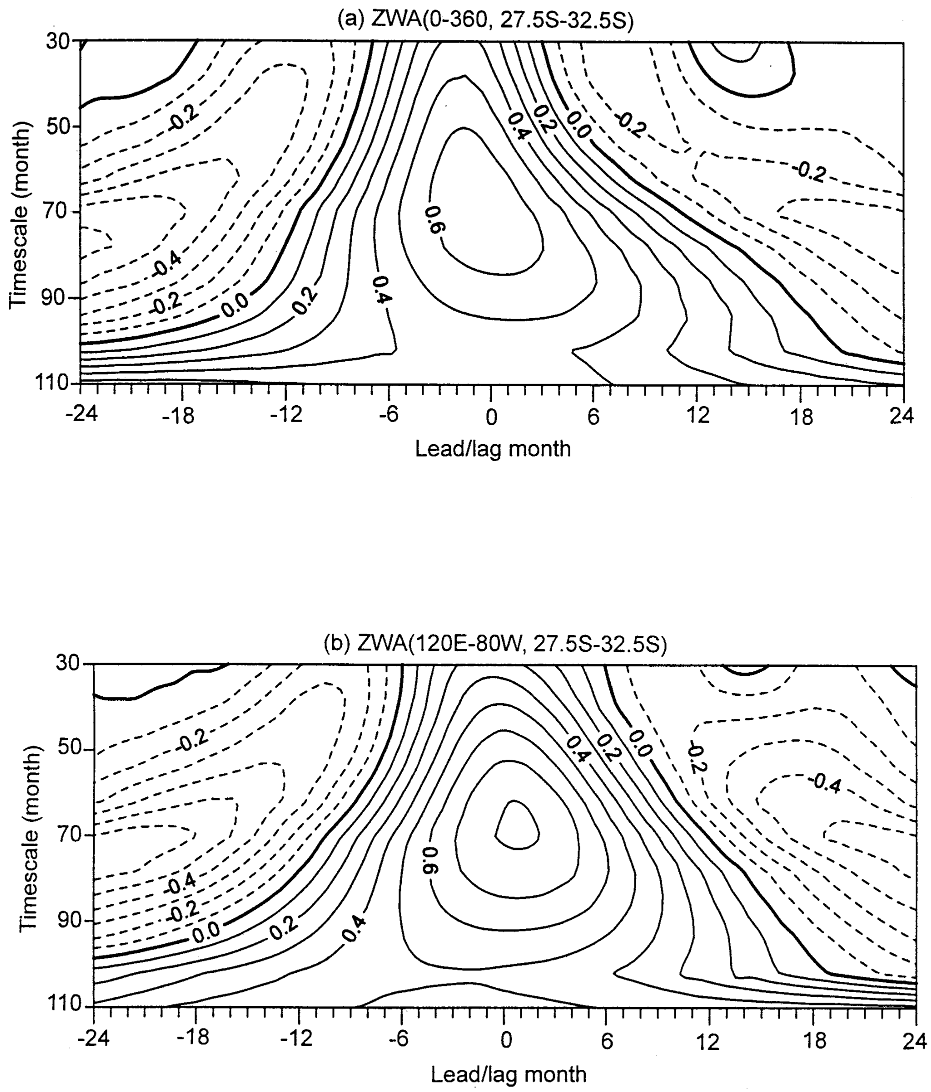

Fig. 10. Same as in Figure 8 but for zonal wind anomalies at regions of (a) the south subtropical zone and (b) the south subtropical Pacific.

anomalies. The leading time is about 8-9 months. The leading cases include the years of 1956-57, 1965, 1971-72, 1975-76, 1982-83, and 1996-97. In Figure 11b for some warming cases, the phase of NINO3 region sea surface temperature anomalies is slightly earlier than that of zonal wind anomalies at the north subtropical Pacific for about 4-5 months, such as 1969-70, 1972-73, 1976-77, 1979-80, 1982-83 and 1991-92. But in 1953-54, 1956-57, 1963-64, and 1997-98, the same variation in phase between zonal wind anomalies and sea surface temperature anomalies is observed from Figure 11b. Apart from the above situations, the same variation in phase can be found in Figure 11c for the zonal wind anomalies at the south subtropical Pacific related to sea surface temperature anomalies at the equatorial eastern Pacific. It is surprising and puzzling to see why there is such a close relationship between NINO3 region sea surface temperature anomalies and zonal wind anomalies at the south subtropical Pacific.

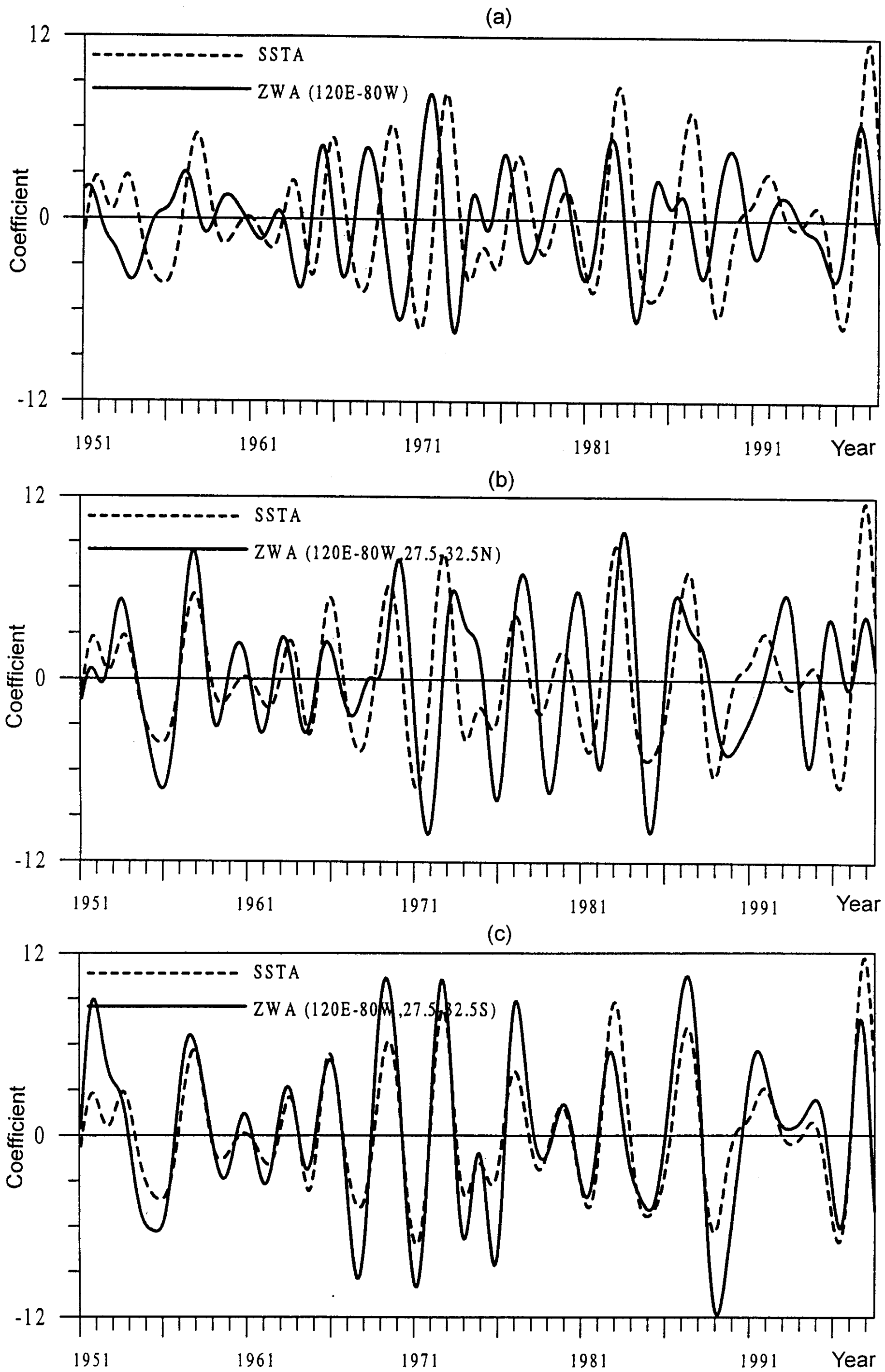

Fig. 11. Wavelet component series of NINO3 region sea surface temperature anomalies and zonal wind anomalies for regions of (a) the equatorial Pacific, (b) the north subtropical Pacific, and (c) the south subtropical Pacific at the 70-month time-scale.

6. *Sea-air interaction of multiple time-space scales*

To better understand the mechanism of El Niño/Southern Oscillation cycle, *Qian and Wang* (1997) proposed that the El Niño/Southern Oscillation cycle is a result of sea-air interaction of multiple time-space scales. These interactions can be briefly described as follows:

(1) Global atmosphere-ocean interaction without continents. It was supposed that the atmosphere and ocean occurred on a rotating earth without continents. In this coupled atmosphere-ocean system, a periodic El Niño/Southern Oscillation cycle can be formed even without regional or local sea-air interaction. The cycle can be described as the fact that the zonal westerly anomaly acts on the global sea surface temperature anomalies through stress and oceanic Ekman effect. The equatorial sea surface temperature anomalies then lead to a trade wind anomaly through an enhancing Hadley cell. In this process, the westerly wind strengthening in the subtropics accompanies the equatorial sea surface temperature rising, but the easterly wind is developing in low latitudes. The strengthening of trade wind leads to sea surface temperature dropping along the equatorial zone through the oceanic upwelling. Within this cycle only the Hadley cell strength changes were considered, while the role of Walker cell and regional cell were omitted. This planetary-scale sea-air interaction can be identified from Figure 11. Figure 11b is relatively more complex than Figure 11c implying that the planetary-scale sea-air interaction is simpler in the Southern Hemisphere than in the Northern Hemisphere due to the complex sea-land topography.

(2) Global atmosphere-ocean interaction with meridian continents. If the global ocean is divided into several basins by meridian continents without topography, the sea surface temperature will rise not only at the equatorial zone but also at the east coast of each basin when anomalous westerly wind acts on all basins. Actual sea surface temperature anomalies in the Pacific can be regarded as an overlap of two components. First are the planetary-scale sea surface temperature anomalies caused by the global ocean-atmosphere interaction. Second are the basin scale sea surface temperature anomalies caused by the anomalous Walker cell. The anomalous Walker cell is a positive feedback for El Niño/Southern Oscillation cycle. In this process the trade wind anomaly caused by Hadley cell strengthening provides a negative feedback mechanism of El Niño/Southern Oscillation cycle.

(3) Regional sea-air interaction. A tropical perturbation can be developed by the interaction of regional sea-air interaction. This regional sea-air interaction was illustrated in our previous work (*Qian et al.*, 2000) and by *Gill* (1980) in his model and zonal wind anomalies analysis in the different parts of the equatorial Pacific.

(4) Atmosphere-earth angular momentum exchange. In the phase of the El Niño event or anti- El Niño event, the mountain torque should be caused by the difference of the sea level pressures crossing two sides of the meridional mountain ranges. The mountain torque will lead the atmosphere-earth momentum exchange and further cause the sea surface temperature anomaly as well as the change in the earth rotation rate (*Qian and Chou*, 1996).

Many theoretical works have illustrated the regional positive feedback of the El Niño/Southern Oscillation cycle (*Gill*, 1980; *Zebiak and Cane*, 1987) while the regional negative feedback was described in our previous work (*Qian et al.*, 2000). The observational fact of regional air-sea interaction has been analysed using different regional zonal wind anomalies in the western, central and eastern Pacific (*Qian et al.*, 2000).

7. Conclusion and discussion

In our data handling, three processes are performed, including vertical integration, zonal average, and climatological departure. As was previously known, the standing Walker/Hadley cells and the travelling regional cell exist in the tropical Pacific. The winds that are associated with the Walker circulation blow in opposite directions in the upper and lower levels so that the reflection of both Walker circulation and regional circulation have been partly filtered out from the vertically-integrated and zonal-averaged values of zonal wind. This then leaves the planetary-scale zonal wind anomalies associated with the anomalous Hadley circulation reflected along the equatorial zone and subtropics. These phenomena can be clearly seen from Figure 1, where the westerly anomaly and easterly anomaly associated with the anomalous Hadley circulation move from the equator to subtropics.

The present paper analyses the relationship between the NINO3 region sea surface temperature anomalies and the tropospheric vertically-integrated zonal wind anomalies in different regions over the global zone and the Pacific Basin for a relatively long period from 1950 to 1999 using the homogeneous NCEP reanalysis data sets. The same variation in phase for zonal wind anomalies between the equatorial zone and the equatorial Pacific, between the subtropical zone and the subtropical Pacific is manifested in the average of the whole troposphere related to the El Niño/Southern Oscillation cycle.

In the period from 1950 to 1998 there have been 13 sea surface temperature warming processes over the equatorial central-eastern Pacific. These warming processes are associated with the zonal wind anomalies at different regions with different phase-lag relationships. Before the El Niño event, the zonal westerly anomalies first appear over the equatorial zone or the equatorial Pacific. The El Niño event takes place when the positive zonal wind anomalies turn to negative one along the equatorial zone or the equatorial Pacific. At the mature phase of El Niño or slightly late the maximum sea surface temperature anomalies, the strong westerly anomalies occur over subtropical latitudes. The wavelet analysis of both zonal wind anomalies along the equatorial zone or the equatorial Pacific and sea surface temperature anomalies in the equatorial eastern Pacific shows that there is a phase-lag relationship between them in the inter-annual time-scale. The phase of equatorial zonal wind anomalies is earlier than that of NINO3 region sea surface temperature anomalies (or El Niño event) for about 5-13 months. A planetary-scale positive/negative feedback scenario that seems to hold during the El Niño/Southern Oscillation cycle can explain this relationship. The positive feedback can be described as the equatorial westerly anomalies leading the sea surface temperature anomalies which rise along the equator, then the westerly anomalies develop along the subtropical zones through the Hadley cell anomaly. The negative feedback can be inferred as the strengthened trade winds (or easterly anomaly) in tropical regions forming upwelling along the equatorial basin and causing the sea surface temperature anomalies to decrease. This paper suggests that the zonal wind anomalies at the equatorial zone and the equatorial Pacific can be used as an early signal for predicting the El Niño/ La Niña events. But physically, the long-term memory of the El Niño/Southern Oscillation cycle is maintained within the ocean while zonal wind anomalies are a sensitive response to wide sea surface temperature anomalies. In the regional sea-air interaction, many previous works have investigated the regional oceanic waves (e.g., *Zebiak and Cane*, 1987). Actually, the observed El Niño/Southern Oscillation cycle is the result of the sea-air interaction of multiple time-space scales.

In the positive-negative feedback process of the planetary-scale sea-air interaction, Hadley circulation anomalies play an important role for transforming angular momentum in different latitudes associated with the El Niño/Southern Oscillation cycle. Positive sea surface temperature anomalies at the equatorial Pacific cause the Hadley circulation to run faster than normal and result in positive zonal wind anomalies at subtropical regions or strengthened subtropical highs. The above phenomenon will strengthen trade winds in the tropics and westerly winds in middle latitudes, so that the interaction of mid-low latitudes can be seen from this process and is also linked with El Niño/Southern Oscillation cycle. The strengthened trade wind is a planetary-scale negative feedback for the El Niño/Southern Oscillation cycle. The planetary-scale Hadley cell anomaly involving the El Niño/Southern Oscillation cycle can also be examined by the meridional wind anomalies in the upper and lower levels. In this paper, we interpret the zonal wind anomaly as an index for the change in the strength of the Hadley cell.

Finally, an El Niño/Southern Oscillation cycle picture could be given as: positive equatorial zonal wind anomalies → positive NINO3 region sea surface temperature anomalies → Hadley cell running faster → positive subtropical zonal wind anomalies → trade wind increasing → negative equatorial zonal wind anomalies → negative NINO3 region sea surface temperature anomalies → Hadley cell running slower → negative subtropical zonal wind anomalies → trade wind decreasing → positive equatorial zonal wind anomalies. This scenario only describes a planetary-scale positive-negative feedback for the El Niño/Southern Oscillation cycle.

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References

Bjerknes, J., 1966. A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature. *Tellus*, **18**, 820-829.

Gill, A.E., 1980. Some simple solutions for heat induced tropical circulation. *Q. J. Roy. Meteorol. Soc.*, **106**, 447-462.

Kalnay, E. et al., 1996. NCEP/NCAR 40 year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437-471.

Lau, K.-M., and H.-Y. Weng, 1995. Climate signal detection using wavelet transform: how to make a time series sing. *Bulletin of the American Meteor. Soc.*, **76**, 2391-2402.

Qian, W.-H. and J.-F. Chou, 1996. Atmosphere-earth angular momentum exchange and ENSO cycle. *Science in China,* Ser. D, **39**(2), 215-224.

Qian, W.-H. and S.-W. Wang, 1997. Multiple time-space scale atmosphere-ocean interactions and improvement of Zebiak-Cane model. *Science in China,* Ser. D, **40**(6), 577-583.

Qian, W.-H., H.-R. Hu, Y.-F. Zhu and Z.-W. Yan, 2000. An analysis of the ENSO cycle associated with the equatorial tropospheric zonal wind anomalies over the Pacific Basin. *Geophysica*, **36**(1), 31-49.

Zebiak, S. E., and M. A. Cane, 1987. A model El Niño-Southern Oscillation. *Mon. Wea. Rev.*, **115**, 2262-2278.