The Relationship between the Asian/ Australian Monsoon and ENSO on a Quasi-Four-Year Scale

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ABSTRACT

The interannual variability of tropical zonal wind and the relationship between ENSO and the Asian/Australian monsoon in different phases are discussed. Results show that the tropical zonal wind strongly couples with the central-eastern Pacific SST on a quasi-four-year scale. During the period of El Niño, the East Asian winter (summer) monsoon is weaker (stronger) and the South Asian summer monsoon is weaker than normal. Conversely, the East Asian winter (summer) monsoon is stronger (weaker) and the South Asian summer monsoon is stronger than normal during the period of La Niña. The anomalous northerly over East Asia induces an anomalous westerly over the western equatorial Pacific, which favors the appearance of positive SST anomalies in the central-eastern Pacific. The development of El Niño requires the persistence of a westerly over the central-eastern Pacific. The convergence between anomalous northerlies from the central North Pacific (not from the East Asian continent) and anomalous southerlies from Northeast Australia favors the persistence of a westerly over the central-eastern Pacific. In particular, the anomalous southerlies from Northeast Australia play a key role in the onset of strong westerly anomalies over the tropical central-eastern Pacific.

Key words: Asian/Australian monsoon, ENSO, quasi-quadrennial oscillation (QQO), tropical zonal wind

1. Introduction

The Asian/Australian monsoon is a planetary-scale circulation system. It includes the South Asian (Indian) monsoon, the East Asian monsoon, and the Australian monsoon component systems. ENSO is a phenomenon of the air-sea interaction. The relationship between ENSO and the Indian/Australian monsoon has been explored in numerous previous studies (Rasmussen and Carpenter 1982; Ropelewski 1987; Joseph and Liebann 1991; Joseph et al. 1994). Chinese scientists have also discussed the relationship between the East Asian monsoon and ENSO. Li (1990) indicated that a strong East Asian winter monsoon favors the occurrence of El Niño in the coming half year. Huang et al. (1996) suggested that East Asian summer monsoon may strongly influence the development of ENSO.

Tomita and Yasunari (1996) and Meehl (1997) presented a quasi-biennial oscillation (QBO) model of the ENSO/monsoon system. The former emphasized the East Asian

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monsoon while the latter stressed the South Asian monsoon. Chen et al. (1991) suggested that the ENSO / monsoon system is a multi–scale phenomenon. A power–spectrum analysis of the Nino 3 index from January 1951 to December 1995, shows obvious quasi–quadrennial oscillation (QQO) and QBO with spectrum peaks at the 45–month and 26–month points. These spectrum peaks reach the 98% significance level based on the red noise spectra. In the singular spectrum analysis (SSA) for the same case, the first six components can express 56.48% of the variance with major periodical nature of the Nino 3 index (dashed line in Fig. 1a). The first four components can express 44.83% of the variance with components 1 and 2

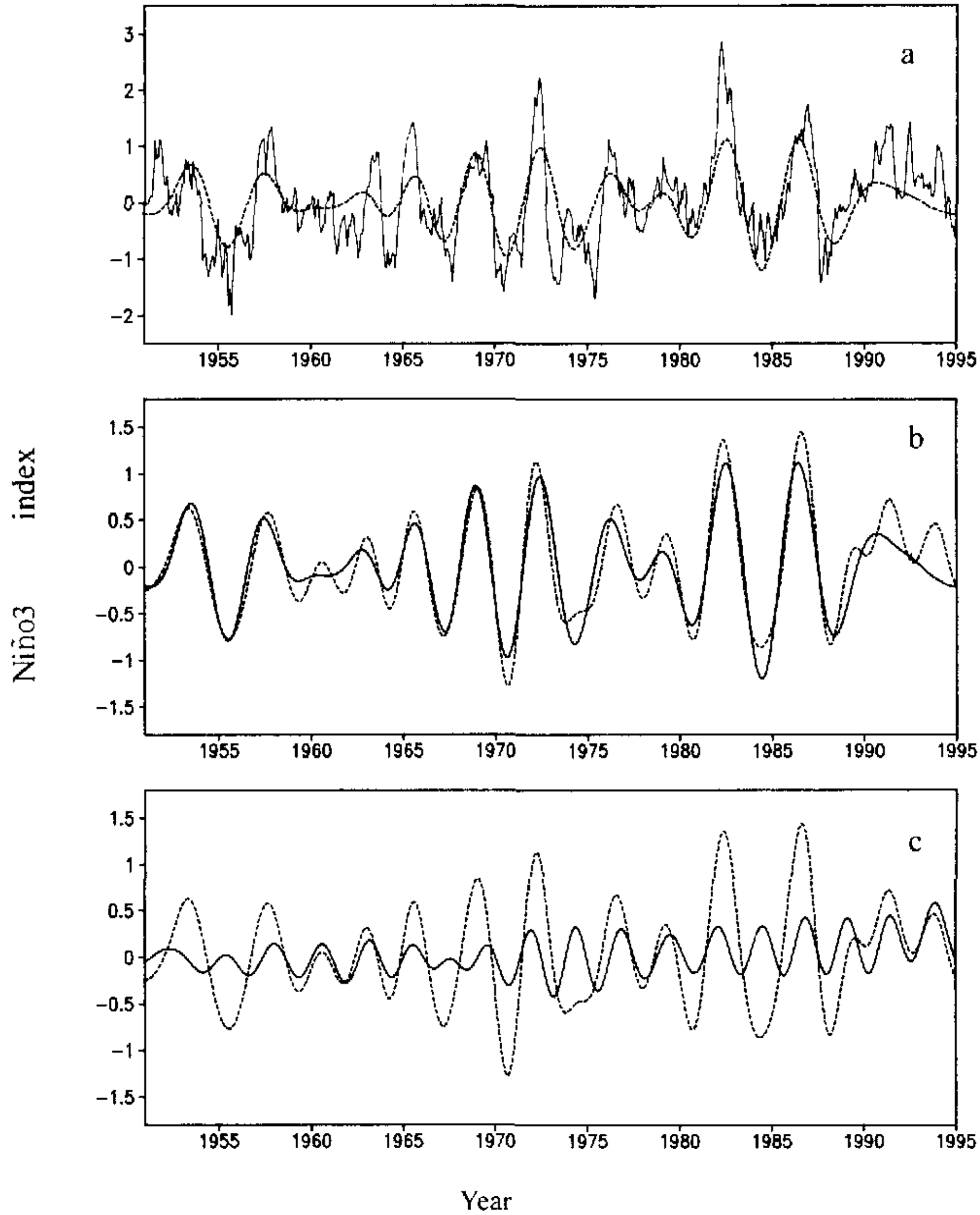

Fig. 1. Result of SSA for Nino 3 index from January 1951 to December 1995: (a) the variability of Nino 3 index (solid) and QQO component (dashed), (b) QQO component (solid) and the first six components (dashed), (c) QBO component (solid) and the first six components (dashed).

responsible for the 48–month mode and components 3 and 4 for the 52–month mode (Fig. 1b). Components 5 and 6 (Fig. 1c) explain 10.6% of the variance and are responsible for the 26–month mode. Figure 1 indicates that QQO is the crucial component of the variability of the Nino 3 index, which determines the time of occurrence and intensity of most El Niño episodes.

It is difficult to understand the ENSO cycle well if only QBO is considered because QQO is the most important component of ENSO variability. Since anomalous SST in the central and eastern equatorial Pacific (CEEP) always persists for more than one year during El Niño (La Niña) events, it is necessary to pay attention to the long periodic behavior of the ENSO cycle. Mu and Li (1999) indicated that the QBO and QQO exist in the interannual variation of the East Asian winter monsoon. In other words, ENSO signals are included in the interannual anomaly of winter monsoon over East Asia. Tan and He (1998), and Tan et al. (1999) discussed the relationship between ENSO and the Asian summer monsoon through studying the air–sea–land interaction on the QQO scale. However, most previous studies paid more attention to the time scale of QBO than QQO, and stressed the relationship between monsoon rains and ENSO. In fact, monsoon rains are not closely related to ENSO in every year. The monsoon is defined as a seasonal reversal of prevailing wind direction. Since a close relationship between abnormal tropical zonal wind and warm SST in CEEP has been demonstrated by observation (Rasmussen and Carpenter 1982), our efforts are therefore focused on the relationship between the Asian / Australian monsoon and ENSO through studying the interaction between abnormal tropical zonal wind and El Niño.

This paper is organized as follows. The datasets used in this study are described in section 2. Section 3 presents the interannual variability of the tropical zonal wind and its relationship with El Niño. Section 4 analyzes the relationship between the Asian / Australian monsoon and the tropical zonal wind. The interaction between the Asian / Australian monsoon and ENSO on the QQO scale is discussed in section 5. Section 6 summarizes the results.

2. Data

The monthly mean zonal and meridional wind components at 850 hPa on a $2.5^\circ \times 2.5^\circ$ grid are from the NCEP / NCAR reanalyzed data set. SST data on a $7.5^\circ \times 4.5^\circ$ grid are from the University of Hawaii provided by Prof. Bin Wang. All data are from January 1951 to December 1995.

3. Interannual variability of tropical zonal wind and its relationship with El Niño

The first step is to define the five subregions over the area from the tropical eastern Indian Ocean to the eastern Pacific (5°N–5°S, 80°E–90°W). The subregions are marked by U1, U2, U3, U4, and U5 (Fig. 2). Zonal wind variations in these five subregions are the time series with 456 samples of monthly zonal wind deviation from the 30–year average (1961–1990). The power–spectrum analysis and SSA show that the five time series of monthly zonal wind anomaly all contain notable QQO with a 95% confidence level.

The next step is to apply a cross–spectrum analysis to the five time series respectively. Results show covariant spectrum peaks located at the 48–month points. The corresponding coagulation spectrum is statistically significant at the level $\alpha = 0.05$ for the F–test (with 456 samples, $M = 96$ as the maximum lag, and $R_c^2 = 0.348$ when $\alpha = 0.05$). Their lead–lag

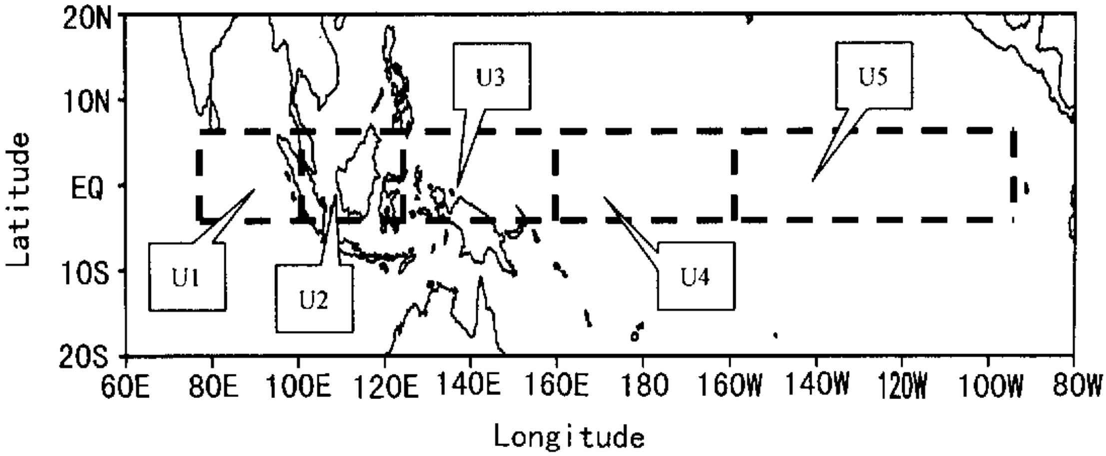

Fig. 2. The definition of five subregions (U1, U2, U3, U4 and U5). All five subregions are bounded by 5°S and 5°N with U1 between 80°–100°E for the eastern equatorial Indian Ocean (EEI), U2 (100°–130°E) for the maritime continent, U3 (130°–160°E) for the western equatorial Pacific (WEP), U4 (160°E–160°W) for the central equatorial Pacific (CEP), and U5 (160°–90°W) for the eastern equatorial Pacific (EEP).

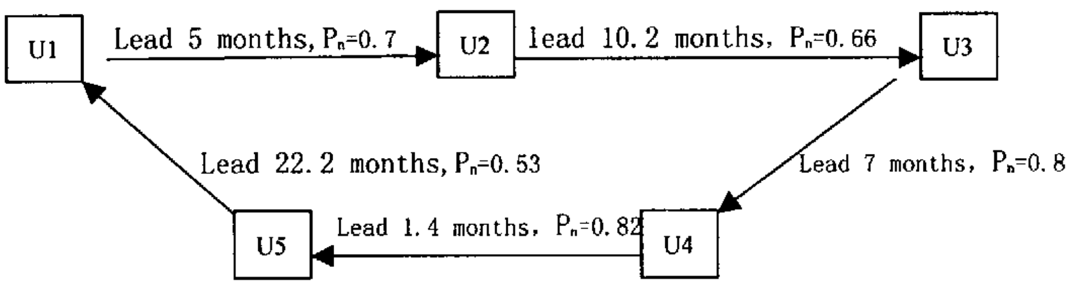

Fig. 3. Schematic illustration of the cross–spectrum analysis.

relations are summarized schematically in Fig. 3.

To understand Fig. 3, an example is presented here. The figure shows that the variation of zonal wind in U1 is five months ahead of that in U2 with $P_n = 0.70$ (P_n as coagulation spectrum square) on QQO. It indicates that the variabilities of zonal wind over different subregions are closely linked each other on the time scale of QQO. For example, the phase variability of zonal wind over EEP is opposite to that over EEI.

In the following, we focus on the relationship between SST in CEP and zonal wind over different subregions. Fig. 4 displays the variation of zonal wind anomalies (ZWA) over the five subregions and sea surface temperature anomalies (SSTA) in the Nino 3 region. The statistical study reveals a negative correlation (with synchronous correlation coefficient of 0.29) between ZWA over U1 and SSTA in the Nino 3 region. The negative correlation indicates that warm SSTA is related to an abnormal easterly over U1. Observation shows that an abnormal easterly (westerly) over U1 always persits in more than one year (figure omitted), which suggests that India experiences not only a weak southwest summer monsoon but also a strong northeast winter monsoon during warm SSTA. The correlation coefficient between ZWA in U3 and SSTA is 0.19 without lagging, but it is 0.4 with ZWA three months ahead of SSTA. It can be seen from Fig. 4c that an abnormal westerly usually occurrs in WEP(U3) before warm SSTA occurs in the Nino 3 region. The abnormal westerly shifts to an abnormal

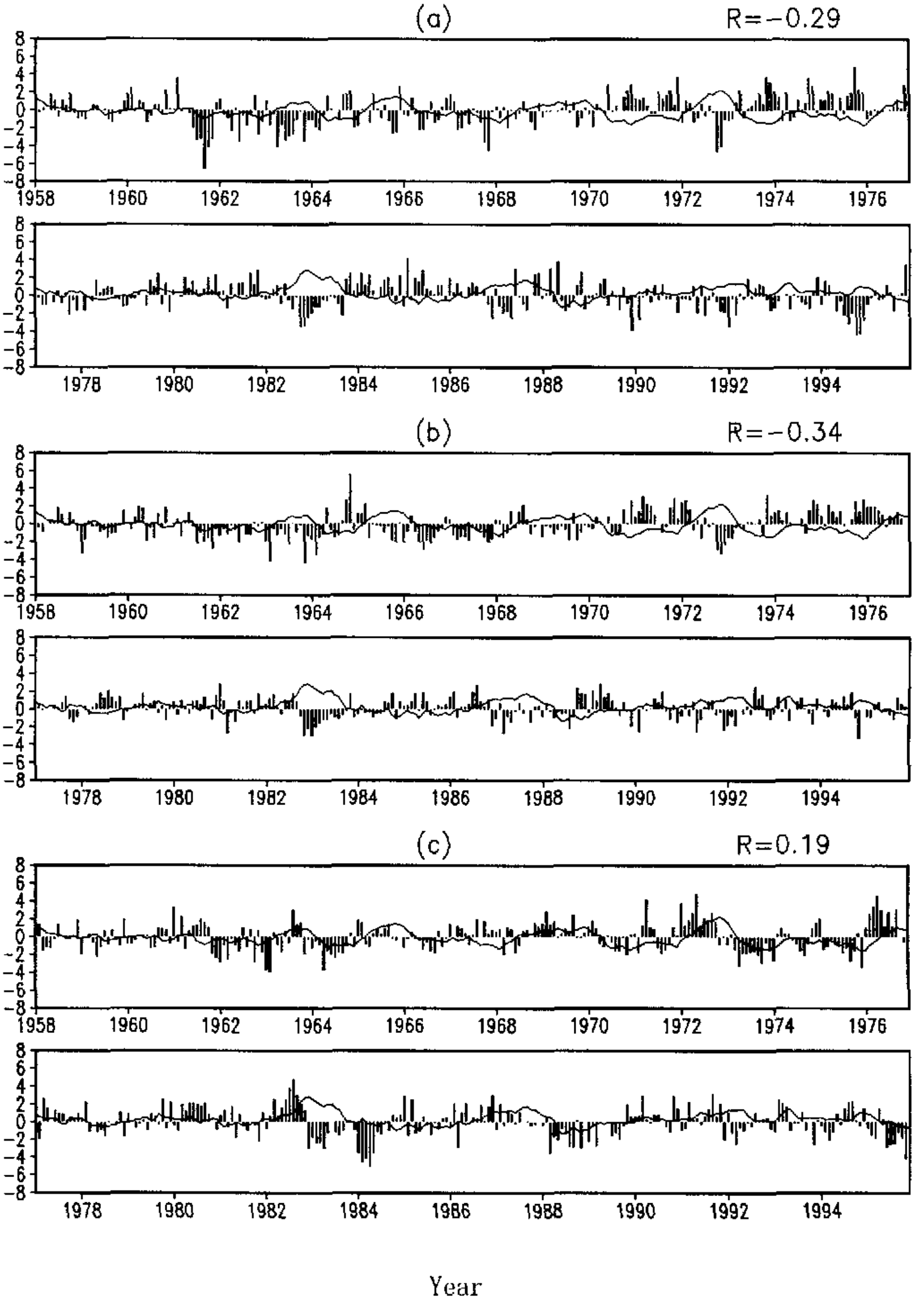

Fig. 4. The variation of zonal wind anomalies over the five subregions (bar, units: m s^{-1}) and SSTA (curve, units: °C) in the Nino 3 region: (a) U1, (b) U2, (c) U3, (d) U4, (e) U5.

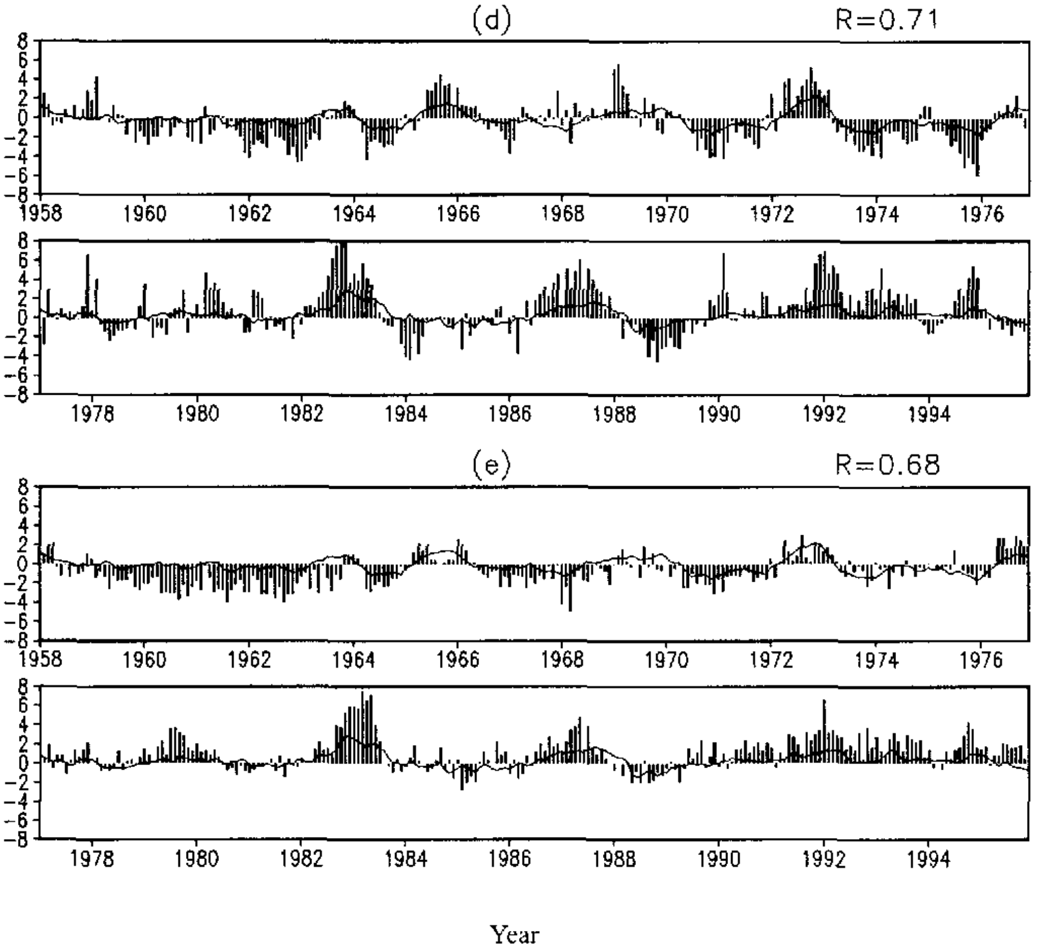

Fig. 4. (Continued).

easterly while warm SSTA reach a maximum. After an abnormal easterly appears in U3, the warm SSTA shift to cold. In other words, an abnormal easterly over U3 is associated with the withdrawal of El Niño. The variation of ZWA over U4 (U5) agrees with Nino 3 SSTA (Figs. 4d,e) with a correlation coefficient of 0.71 (0.68) without lagging and 0.73 (0.71) with ZWA one to two months ahead of SSTA. Usually, warm SSTA accompany the abnormal westerly over U4 area. The stronger the westerly is, the warmer the SSTA. However, during the period from the winter of 1958 to the spring of 1959 and from the autumn to the winter in 1969, no prominent warm SSTA appears in the Nino 3 region, although a strong westerly occurs over U4. By referring back to Fig. 4e, it can be found that the abnormal westerly in U5 is weak and discontinuous during the periods mentioned above. So, an abnormal westerly over WEP is only a part of the signal of warm Nino 3 SSTA. Warm Nino 3 SSTA is more closely related to an abnormal westerly over CEP and EEP, especially over EEP.

It is worth noting that abnormal zonal wind over different areas influences SST in various ways. The eastward propagation of the warm sea water due to the eastward−propagating warm Kelvin wave exited by the westerly anomalies over WEP favors the warm SST appearance over CEP and EEP. In the CEP, a westerly would be conducive to weaken cool upwelling through suppressing Ekman pumping, which is favorable for the persistence of warm

SST. The persistence of warm SSTA may further contribute to the occurrence and development of El Niño.

In summary, the interaction process between zonal wind and El Niño on QQO can be described as follows. The abnormal westerly over EEI occurs two years prior to the onset of El Niño. Five months later, an abnormal westerly also appears over the Maritime continent. After 10 months, the abnormal westerly controls the WEP, which leads to warm SST in CEP and EEP due to the eastward spread of Kelvin wave and warm−pool sea water. Seven months later, an abnormal easterly dominates CEP and EEP, which induces the occurrence of positive SSTA in these areas by suppressing Ekman pumping. These results imply that the abnormal westerly over CEP and EEP plays a key role in El Niño onset.

4. Relationships between the Asian/ Australian monsoon and the tropical zonal wind

In the above sections, the spatial and temporal characteristics of the tropical zonal wind and its relationship with El Niño have been discussed. Results show ZWA over the tropical area is closely linked to El Niño and expresses notable QQO. In this section, we try to discuss the relationships between zonal and meridional wind, and the interaction between meridional wind and SSTA in the CEP and EEP.

The distribution of the correlation coefficient between meridional wind and zonal wind shows that the abnormal westerly in U1 is closely associated with the convergence of meridional wind to the west of 80°E and divergence to the east of 80°E (Fig. 5). This circulation pattern is related to the weak summer or strong winter Indian monsoon. The abnormal westerly in U2 is related to the abnormal northerly over the northwestern Pacific and the region from the East China to South China Sea and the abnormal southerly over South India and northeast Australia. Fig. 5b indicates that the abnormal westerly in U2 accompanies a cyclone pair, which is located at Australia and the area from East China to the northwestern Pacific. The abnormal westerly over WEP is linked to the convergence between the northerly from the Philippines and the southerly from North Australia. The abnormal westerly above CEP and EEP is also related to the convergence between meridional winds in this area (Figs. 5d and 5e). All these suggest that the behavior of tropical zonal wind is closely related to the circulation pattern in the Southern and Northern Hemispheres, which agrees with the conclusions from a previous study (Zhu and Chen 2000).

Further study was employed to understand the relationship between abnormal zonal wind over CEP (EEP) and abnormal meridional wind. The statistical result shows that the correlation coefficient between the averaged meridional wind over the area 2.5°−30°N, 130°−160°E (VN1, Fig. 6) and averaged zonal wind in U4 is −0.39, and the correlation coefficient between the averaged meridional wind over the region of 2.5°−30°S, 130°−160°E (VS1) and U4 is −0.61. The correlation between U4 and the intensity of meridional convergence / divergence represented by V1 = VS1−VN1 is 0.68, which is larger than the critical value with a 99% confidence level (see Fig. 7). These results mean that the stronger the meridional convergence over WEP is, the larger the abnormal westerly above CEP. The abnormal meridional winds from northern Australian play a more important role in convergence.

Similarly, the correlation between VN2 (averaged meridional wind over the region 2.5°−30°N, 160°E−170°W) and U5 (averaged zonal wind in U5) is −0.478, and the correlation

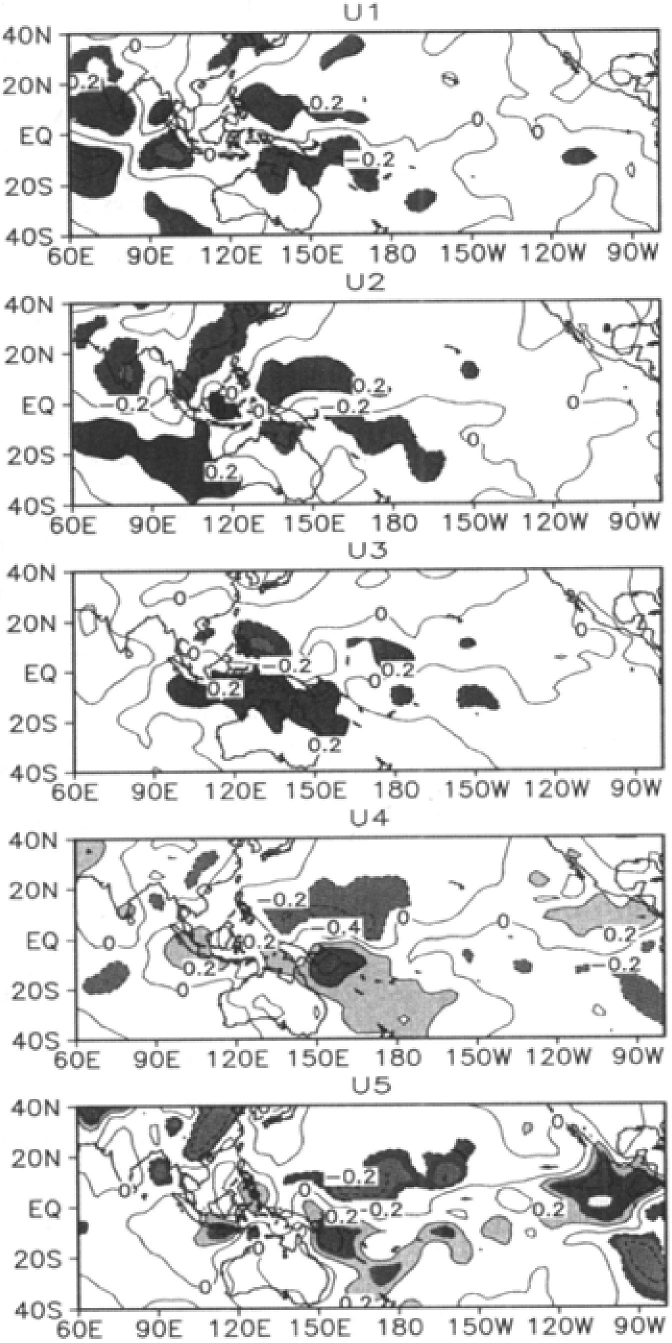

Fig. 5. The distribution of the correlation coefficient between meridional wind and zonal wind over U1, U2, U3, U4, U5, respectively (shaded means the values larger than 0.2).

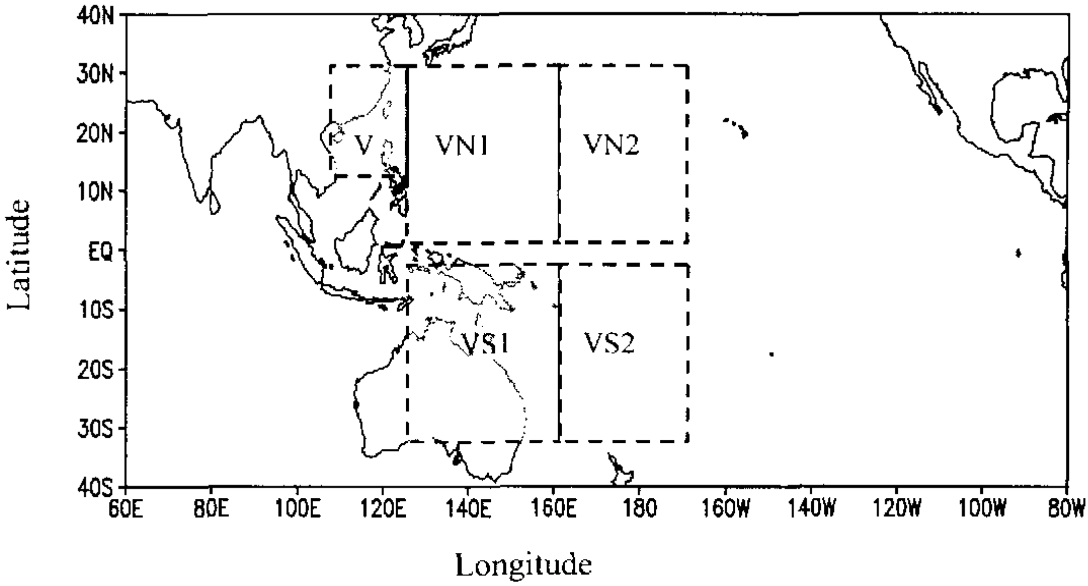

Fig. 6. The definition of subregions V (110°–130°E, 10°–30°N), VN1 (2.5°–30°N, 130°–160°E), VN2 (2.5°–30°N, 160°E–170°W), VS1 (2.5°–30°S, 130°–160°E) and VS2 (2.5°–30°S, 160°E–170°W).

between VS2 (averaged meridional wind over the region 2.5°–30°S, 160°E–170°W) and U5 is 0.467. The correlation between V2 (VS2–VN2) and U5 is 0.542, which is also larger than the critical value with a 99% confidence level. This suggests that the stronger the meridional convergence over CEP is, the larger the abnormal westerly over EEP. Such a condition favors the warm SSTA in this area (Fig. 8).

On the whole, the tropical zonal wind is closely related to the Asian / Australian monsoon. The abnormal westerly over the EEI is associated with the strong summer or weak winter Indian monsoon. The abnormal westerly over the maritime continent always accompanies the abnormal cyclone located over Australia and the area from East China to the northwestern Pacific. The abnormal westerly over WEP is related to the convergence between the northerly from the Philippines and the southerly from northern Australia. The abnormal westerly over CEP and EEP is linked to the meridional wind convergence over the same area. The relation between the abnormal southerly from Northeast Australia and the abnormal westerly over the central–eastern Pacific is notable.

5. Interaction between the Asian/ Australian monsoon and ENSO on QQO

The results of the previous sections suggest that zonal wind anomalies over the tropics are closely related to the occurrence, development, and dissipation of El Niño episodes on the time scale of QQO. The abnormal westerly over CEP and EEP corresponds to the occurrence and development of El Niño. Meridional convergence in CEP is associated with the abnormal westerly over this area.

From Fig. 5, it is apparent that meridional wind over East China is also related to tropical zonal wind. Li (1990) discussed the relationship between the East Asian winter monsoon

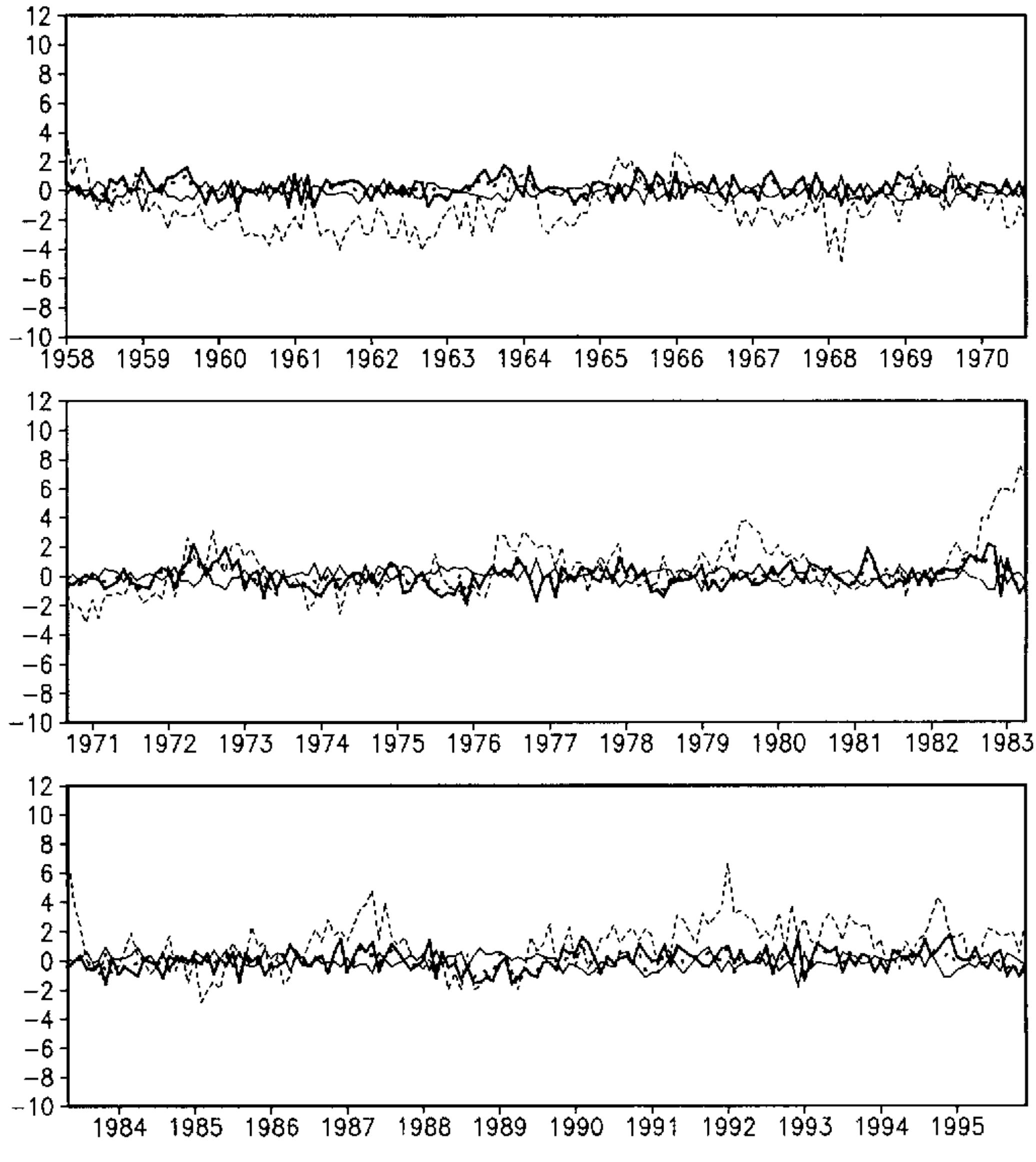

Fig. 7. The variations of VN1 (dashed), VS1 (dotted), V1 (thin solid), and U4 (thick solid), units: m s^{-1}.

and ENSO, and suggested that a strong East Asian winter monsoon favors the occurrence of El Niño in the next half year. Huang et al. (1996) proposed that the East Asian summer monsoon might play an important role in the ENSO cycle. To verify the role of the East Asian monsoon in ENSO events, an investigation is carried out on the 850 hPa meridional wind anomaly (deviation from the five–point moving average) over the East Asian coastal area (110°–130°E, 10°–30°N, V in Fig. 6). The results show that in most cases, the anomalous northerly on the East Asian coast is followed by a La Niña event, and it persists for more than one year. In other words, a persistent anomalous northerly prevails off East Asia, which is associated with the strong East Asian winter monsoon and weak East Asian summer monsoon prior to the onset of El Niño. Sun and Sun (1995, 1996) suggested that a strong winter

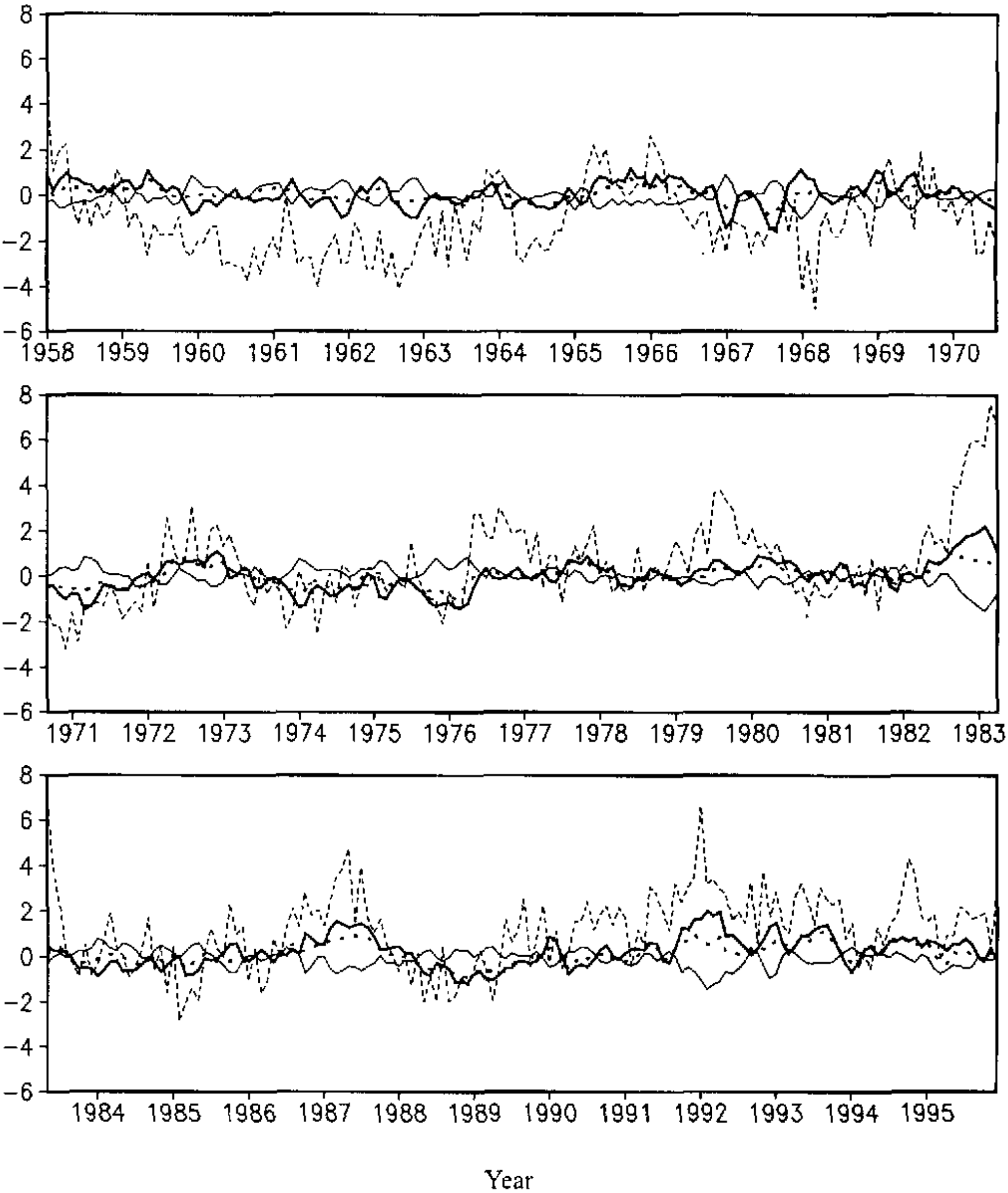

Fig. 8. The variations of VN2 (dashed), VS2 (dotted), V2 (thin solid) and U5 (thick solid), units: m s^{-1}.

monsoon may induce the occurrence of a weak summer monsoon in the next year over East Asia through the air–sea interaction. However, some years exist in which the northerly anomalies occurred over East Asia but no El Niño event developed in the following year. For example, although northerly anomalies prevailed off the East Asia coast from 1979 to 1980, no following El Niño appeared. This means that some other factors must also be present. The analyses in section 4 suggest that the Australian monsoon may play an important role. In our opinion, it is necessary to consider the joint effects of the Asian / Australian monsoon on the ENSO cycle.

Further cross–spectral analysis, applied to the averaged meridional wind anomalies over V and the Niño 3 index (with a sample of 456 months, maximum lag of 96 months), shows a dominant coupled variability with a quasi–four–year period. The covariant spectrum peak is at periods of 48 months and the corresponding coagulation spectrum is 0.59 (in the F–test, $R_c^2 = 0.348$ when $\alpha = 0.05$), reaching the level of significance. In this case, the variability of the meridional wind is about 3–4 months ahead of the variation of SST in the Nino 3 region. The teleconnection circulation pattern also shows that the position of the polar front is further south than normal and the intensity of the East Asian trough is stronger than normal over East Asia, which induces the emergence of an abnormal northerly over East China. That is, the abnormal northerly over East Asia is closely related to the anti–PNA pattern.

In summary, the relationships between ENSO and the Asian / Australian monsoon can be described as follow. The south Asian summer (winter) monsoon is stronger (weaker) than normal during the period of La Niña. The variation of the teleconnection pattern forced by abnormal SSTA leads to the persistence of an abnormal northerly over East Asia. A strong winter monsoon is followed by a weak summer monsoon through the air–sea interaction. The abnormal northerly benefits the occurrence of an abnormal westerly over WEP, which triggers the eastward propagation of Kelvin wave and warm SST to EEP. This will result in the withdrawal of La Niña. The westerly over CEP and EEP is related to the convergence of the southerly from Australia and the northerly from the central North Pacific, and it weakens the cool upwelling by suppressing Ekman pumping. The persistence of warming SST in CEEP contributes to the development of El Niño. The northerly over East Asia is of benefit to the onset of the abnormal westerly over WEP. However, the development of El Niño needs the persistence of an abnormal westerly in CEP. The convergence between the northerly from the central northern Pacific (not from the eastern Asian continent) and the southerly from Australia contributes to the persistence of the abnormal westerly over CEEP. In particular, the Australian monsoon plays a key role in the persistence of the abnormal westerly over CEEP.

6. Summary

The interannual variability of the tropical zonal wind and its relationship with El Niño is investigated. The relationship between the Asian / Australian monsoon and the tropical zonal wind, and that between the Asian / Australian monsoon and ENSO on a QQO scale is also discussed. The results show:

(1) A prominent Quasi–quadrennial oscillation can be identified in the variation of zonal wind in the tropical area and ENSO. The tropical zonal wind is strongly associated with SST in CEP on the time scale of QQO.

(2) *During the period of El Niño, the East Asian winter(summer) monsoon is weaker* (stronger) than normal, and the South Asian summer monsoon is weaker than normal. Conversely, during the period of La Niña, the East Asian winter (summer) monsoon is stronger (weaker) than normal, and the South Asian summer monsoon is stronger than normal.

(3) The preceding northerly associated with the East Asian monsoon is partly responsible for the occurrence of El Niño. The convergence between the northerlies from the central North Pacific(not from the East Asian continent) and the southerlies from northeast Australia can trigger strong westerly anomalies over the CEP and EEP, which will excite El Niño.The anomalous southerlies from North Australia play a more important role in the development of the westerly over the CEP and EEP.

This paper analyzes the relationship between ENSO and the Asian / Australian monsoon in view of the air–sea interaction, and stresses the joint effects of the Asian / Australian monsoon on the ENSO cycle. Further studies are necessary to explore the relationship between ENSO and the monsoon in detail from the viewpoint of land–atmosphere– ocean interactions.

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亚澳季风异常与 ENSO 准四年变化的联系分析

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摘 要

分析了赤道地区纬向风的年际变化特征，以及亚澳季风与 ENSO 在各个位相的联系。结果表明：赤道纬向风变化与中东太平洋海温变化在准四年周期上是强烈耦合的；在 El Niño 期间东亚冬季风弱，夏季风强，而南亚夏季风弱，反之，在 La Niña 期间东亚冬季风强，夏季风弱，而南亚夏季风强；东亚地区的异常北风有利于西太平洋西风异常爆发，使得东太平洋海温升高，但只有随后在中东太平洋出现持续性西风异常，El Niño 才能发展，其中来自太平洋中部的异常北风（并不是来自东亚大陆地区）和南太平洋中部的异常南风的辐合对中东太平洋出现持续性西风异常起重要的作用，尤其是澳大利亚东北部的季风异常的影响更为显著。

关键词：亚澳季风，ENSO，准四年振荡，赤道纬向风