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Remote and Local SST Forcing in Shaping Asian-Australian Monsoon Anomalies

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Abstract

The most striking feature of the Asian-Australian monsoon associated with the El Niño teleconnection is the evolution of anomalous anticyclones over the western North Pacific (WNP) and southeast Indian Ocean (SIO). In this study we investigated the relative role of remote and local SST forcing in shaping the monsoon anomalies with an atmospheric general circulation model (AGCM). Four idealized AGCM experiments were designed to isolate the effect of anomalous SST forcing from the tropical eastern Pacific, tropical western Pacific and tropical Indian Ocean. In the first experiment observed SST is specified in the tropical eastern Pacific, while climatological monthly mean SST is specified elsewhere. In the second experiment the observed SST is specified in the tropical western Pacific only. In the third experiment realistic SST is specified in both the tropical Indian Ocean and eastern Pacific. In the fourth experiment the observed SST is specified across the tropical Indian and Pacific Oceans.

Our numerical experiments indicate that the anomalous anticyclone in the WNP is initiated by local SST anomaly (SSTA) forcing in northern fall, and further maintained by both the remote (El Niño) and local SSTA forcing. The initiation of the anomalous anticyclone over the SIO is primarily attributed to the local SSTA, though the remote forcing from the eastern Pacific also plays a role, particularly in 1997. The numerical experiments reveal a seasonal-dependent character of inter-basin teleconnection between the tropical Pacific and Indian Oceans, this is, the Indian Ocean SSTA exerts a significant impact on the western Pacific wind in northern summer and fall of the El Niño developing year, whereas the eastern Pacific SSTA has a greater impact on the Indian Ocean wind during the mature phase of the El Niño (boreal winter), even though the central Pacific heating is stronger in boreal summer. A special feature for 1997–98 El Niño is that the meridional wind anomaly over the Indian Ocean in DJF is primarily driven by local SSTA forcing, while the zonal wind component is forced by the remote SSTA in the eastern Pacific.

1. Introduction

The El Niño-Southern Oscillation (ENSO) has been considered as a major factor influencing the interannual variability of the Asian-Australian monsoon (AAM) (see Webster et al. 1998 for a review). Walker (1923, 1924) first recognized the effect of the Southern Oscillation on the Indian monsoon. Since then, a number of studies have been conducted to elucidate the AAM-ENSO relationship (e.g., Yasunari 1990; Webster and Yang 1992; Nigam 1994; Ju and Slingo 1995; Lau and Yang 1996;

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Soman and Slingo 1997; Kawamura 1998; Kumar et al. 1999; Slingo and Annamalai 2000; Chang et al. 2001). The AAM system exhibits complex regional characteristics. For instance, during the El Niño developing year the Indian summer monsoon rainfall tends to be deficient (Rasmusson and Carpenter 1983; Shukla and Paolino 1983; Webster et al. 1998; Lau and Nath 2000), while the western North Pacific (WNP) monsoon is enhanced (Wang et al. 2003). The Meiyu/Baiu front along central China and Japan is strengthened 6 months after the peak of El Niño (Fu and Teng 1988; Chen et al. 1992; Shen and Lau 1995; Chang et al. 2000; Lau and Weng 2001). A strong (deficient) monsoon rainfall in Australia often follows a strong (deficient) Indian summer monsoon (Meehl 1987; Yanai and Liu 2004; Zhang and Li 2004).

A key question related to the monsoon-ENSO relationship is how the El Niño remotely affects the Asian monsoon. The anomalous Walker circulation, with abnormal subsidence over the monsoon sector, was recognized as a major teleconnection mechanism (Shukla and Wallace 1983; Palmer et al. 1992). Wang et al. (2003) emphasized the importance of the monsoon-warm ocean interaction. They attributed an equatorial asymmetric monsoon response to El Niño forcing to the hemispheric asymmetry of vertical shear of the mean flow.

The left panels of Fig. 1 illustrate the seasonal evolution of composite rainfall and low-level wind anomalies (defined as monthly deviations from a climatological annual cycle) associated with the ENSO. The composite is based on 12 major El Niño episodes during 1950–1999. The most pronounced feature is the evolution of two anomalous anticyclones and accompanying precipitation anomalies over the Southeast Indian Ocean (SIO) and WNP, respectively. During JJA of the El Niño development year, the low-level circulation anomalies are characterized by an elongated anticyclonic ridge extending from the maritime continent to the southern tip of India. Associated with this anticyclonic ridge is a tilted belt of pronounced anomalous westerlies extending from the Bay of Bengal to the WNP, suppressed convection over the maritime continent, and enhanced convection over the Philippine Sea. Convection southwest of Sumatra is severely suppressed, which induces a notable cross-equatorial flow west of Sumatra, and a weak anticyclonic cell in the SIO. In SON, the SIO anticyclone grows explosively, leading to a giant anticyclonic ridge dominating the Indian Ocean, with the anticyclone center at 10°S, 90°E. Intense easterly anomalies develop along the equatorial Indian Ocean; convection is suppressed in the eastern Indian Ocean while enhanced in the western Indian Ocean—a typical dipole (or zonal mode) structure (Webster et al. 1999; Saji et al. 1999). Easterly anomalies and drought develop over the Maritime Continent and north of Australia. A new anomalous low-level anticyclone starts to form in the vicinity of the Philippines. In DJF, the low-level circulation anomalies are dominated by two subtropical anticyclonic systems, located in the SIO and the WNP, respectively. The former is a result of the weakening and eastward retreat of the SIO anticyclone from boreal fall, while the later results from the amplification and eastward migration of the Philippine anticyclone. In MAM, there is a similar anomaly pattern in the WNP, characterized by the pronounced WNP anomalous anticyclone. The intensity of the WNP anticyclone, however, decreases toward summer. By this season, the SIO anticyclone has completely disappeared. During the JJA of the El Niño decaying year, subsidence controls the Philippine Sea, signifying weakening of the summer monsoon over the WNP. The anomaly pattern exhibits nearly opposing polarities with that in the summer of the previous year, indicating a strong tendency of a tropospheric biennial oscillation (TBO, see Meehl 1993; Chang and Li 2000; Li et al. 2001ab; Wang et al. 2003; Kawamura et al. 2003).

Given the distinctive life cycles of the anomalous anticyclones, a key question to be addressed is what is the relative role of remote and local SST anomaly (SSTA) forcing in contributing to the observed evolution characters. Wang et al. (2000) and Lau and Nath (2003) pointed out the importance of local air-sea interactions in maintaining the WNP anticyclone from northern winter to subsequent summer. Wang and Zhang (2002) suggested that the anomalous anticyclone in the WNP is initiated by southward invasion of cold surges from the Asian continent in late northern fall. Watanabe and Jin (2002) and Kug and Kang (2004), on

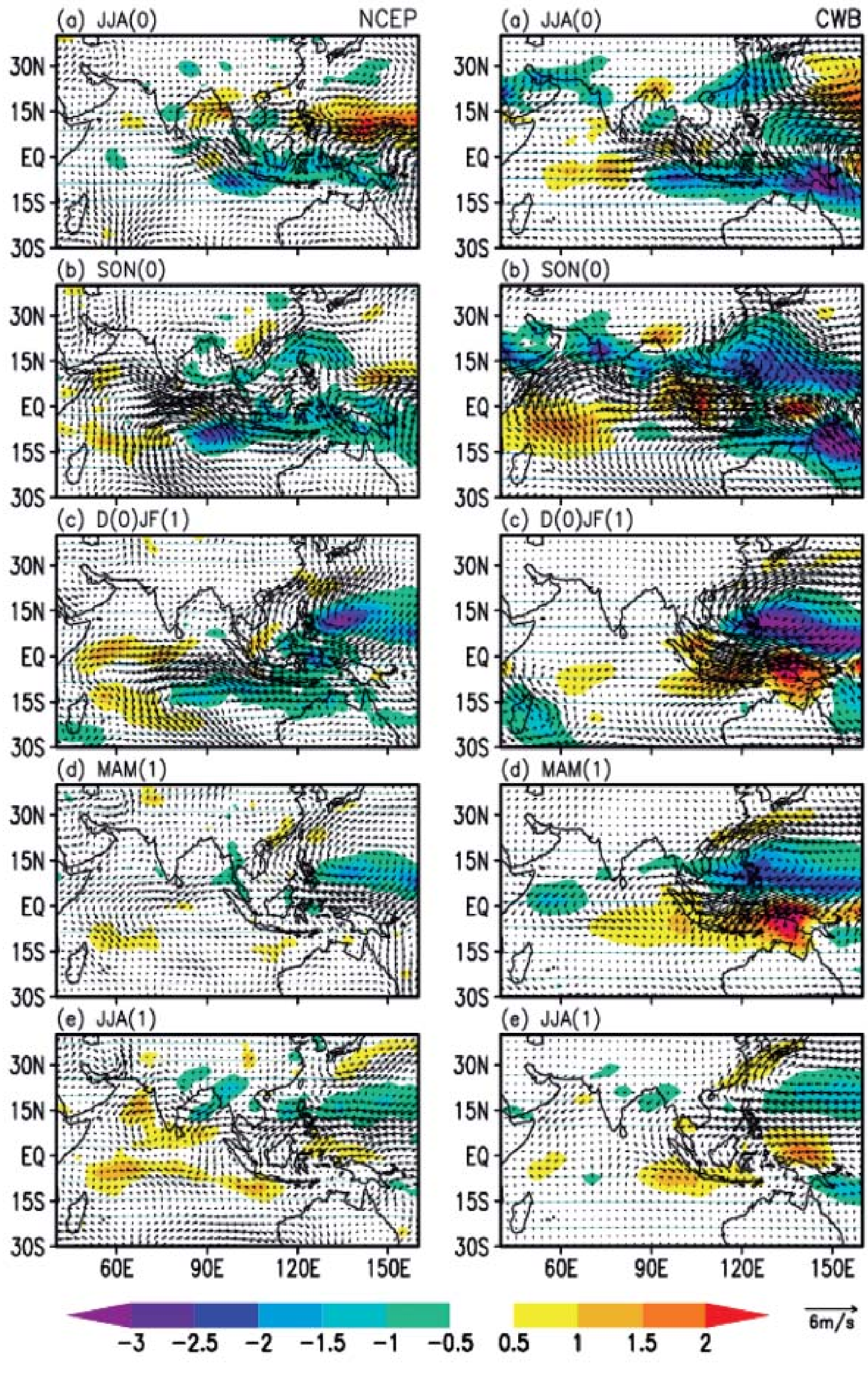

Fig. 1. Composite evolution of precipitation (shading, unit: mm day^{-1}) and 925 mb wind (vector) anomalies for JJA(0), SON(0), DJF(1), MAM(1) and JJA(1). The composite is based on 12 major El Niño episodes during 1950–1999 with use of the NCEP/NCAR reanalysis data (left panels) and the 10-ensemble average of the CWB model simulation (right panels). JJA(0) and JJA(1) denote the summer season of the El Niño developing and decaying years, respectively.

the other hand, emphasized the role of the Indian Ocean SSTA in the initiation process.

The objective of this study is to investigate the relative role of the remote versus local SSTA in causing the circulation anomalies over the tropical Indian and western Pacific Oceans. Our strategy is to examine the response of an atmospheric general circulation model (AGCM) to regional SSTA forcing. As demonstrated in the next section, the AGCM used in this study is capable of reproducing the large-scale El Niño teleconnection pattern in the monsoon region. The rest of this paper is organized as follows. In section 2 we describe the model and control simulation results. In section 3 we describe numerical experiments. The idealized numerical model results are presented in section 4. Finally, a conclusion is given in section 5.

2. The model and a control simulation

The model used in this study is a global AGCM developed at the Central Weather Bureau (CWB) in Taiwan (hereafter the CWB model). The dynamic part of this AGCM is a global spectral model with a sigma coordinate in the vertical. The forecast variables include vorticity, divergence, surface pressure, virtual potential temperature, and specific humidity. Orszag (1970) spectral method is used in horizontal, and Arakawa and Suarez (1983) vertical difference method is employed in the vertical. The time integration model adopts a semi-implicit method. The occurrence of negative moisture, due to the use of the spectral method, is compensated by borrowing moisture from the layer below, and the model bottom layer borrows moisture from the Earth surface. A 4^{th} order horizontal diffusion is used in vorticity, divergence, virtual potential temperature, and specific humidity.

The model contains a number of physical parameterization schemes. The similarity theory is used to calculate the flux exchange at the surface. A 1 1/2-order E-epsilon closure K theory (Deterning and Etling 1985) is used to simulate the vertical turbulence mixing. The radiation scheme developed by Harshvardhan et al. (1987) is adopted in the model with the effects of H_2O, CO_2 and O_3. The cloud model is similar to that of Slingo (1987), with maximum vertical overlapping in convective clouds and random overlapping for other types of clouds. A relaxed Arakawa and Schubert scheme developed by Moothi and Suarez (1992) is used for cumulus convection parameterization. The model also includes large-scale precipitation and shallow convection. The large-scale precipitation parameterization removes the over-saturated condition in the model. The excessive moisture will condense and fall into the next model level as rainfall. The shallow convection scheme of Tiedtke (1984) is used to account the non-precipitation shallow convection generated by orography. To simulate the vertical momentum flux generated by sub-grid scale terrain, the gravity wave drag scheme of Palmer et al. (1986) is included. Surface temperature and moisture fields are calculated based on surface heat and moisture budget equations that include the effect of the deep soil modulation. The surface roughness over the ocean is a function of friction velocity, whereas it is prescribed over land.

For the current study a T42L18 resolution was employed. For a control run, the model was integrated for 50 years, with 10 ensemble members (each with a slightly different initial condition). Observed monthly mean SST fields for 1950–1999 are specified as a lower boundary condition.

The model is capable of simulating some fundamental features of the annual cycle of the atmospheric circulation in the AAM region. In northern summer, the low-level atmospheric circulation in the region is characterized by marked northward cross-equatorial flows; intense convection in the monsoon trough is associated with low-level westerlies. Along the latitude band of 10–20°N, four convection centers appear in the eastern Arabia Sea, Bay of Bengal, South China Sea, and the WNP. Over the Indian Ocean sector, two maximum convection zones are observed in boreal summer, one along the monsoon trough at 15–20°N and the other over the equatorial region. In the northern winter, strong convection moves to the maritime continent/northern Australia, and the South Indian Ocean convergence zone. The low-level winds blow from northeast to southwest along the coast of the Asian continent, cross the equator, and converge into the South Indian Ocean convergence zone. All these features are well simulated by the CWB model.

The right panels of Fig. 1 show the 10-

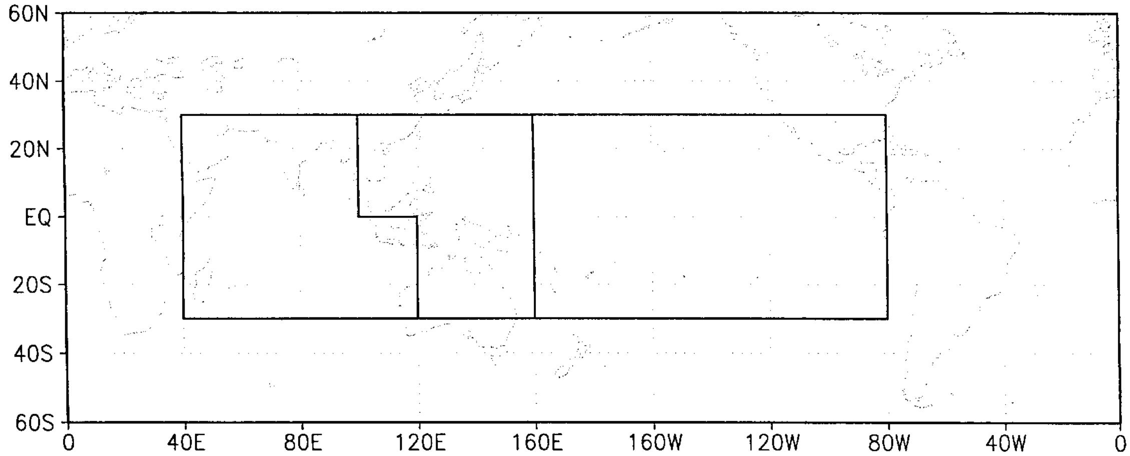

Fig. 2. Geographic location of three regions representing the tropical eastern Pacific, tropical western Pacific and tropical Indian Ocean.

ensemble averaged simulation of the El Niño teleconnection patterns in the AAM region. Compared to the observed composite (the left panels of Fig. 1), the model did capture the large-scale circulation pattern and evolution reasonably well. For instance, it captures the structure, initiation, and evolution of the two anomalous anticyclones over the SIO and WNP. Similar to the observed, the simulated SIO anomalous anticyclone develops rapidly in summer and reaches its mature phase in fall. The anomalous WNP anticyclone is initiated in northern fall over the Philippines, and persists for subsequent three seasons till next summer. The anomalous rainfall patterns are in general consistent with the anomalous low-level wind fields, although they have systematic errors in maritime continent regions.

3. Experiment design

Given that the CWB model is capable of reproducing realistic ENSO teleconnection patterns, we investigate the relative role of the remote and local SSTA forcing in generating these anomalous circulation patterns. We specially design the following four experiments in order to isolate the role of the SSTA forcing from the tropical eastern Pacific, tropical western Pacific, and tropical Indian Ocean.

In the first experiment (Exp1), observed SST is specified in the tropical eastern Pacific (160°E–80°W, 30°S–30°N) while the climatological monthly mean SST is specified elsewhere. The purpose of this experiment is to examine the sole effect of the remote eastern Pacific SSTA forcing. In the second experiment (Exp2), observed SST is specified in the tropical western Pacific (including the maritime continent and the South China Sea, 100–160°E, 0–30°N and 120–160°E, 30°S–0°N) while the climatological SST is specified in other regions. The purpose of this experiment is to examine the effect of the local SSTA in the generation and maintenance of the WNP anticyclone, and the possible role of the western Pacific SSTA on circulation anomalies in the Indian Ocean. In the third experiment (Exp3), realistic SST fields are specified in both the tropical Indian Ocean (40–120°E, 30°S–30°N) and eastern Pacific (160°E–80°W, 30°S–30°N), while the climatological SST is specified elsewhere. The purpose of Exp3 is to reveal the role of the Indian Ocean SSTA (by comparing with Exp1). As we know, the Indian Ocean SSTA may have the following two effects. One is to initiate local atmospheric anomalies over the Indian Ocean. The other is to modulate atmospheric convection over the maritime continent that may further affect the circulation over the WNP. Figure 2 shows the geographic location of the three box regions. In the fourth experiment (Exp4), we specify the observed SST in all three regions (i.e., tropical Pacific and Indian Ocean regions), while the climatological SST is specified elsewhere. By comparing this experiment with the control experiment, one may estimate the re-

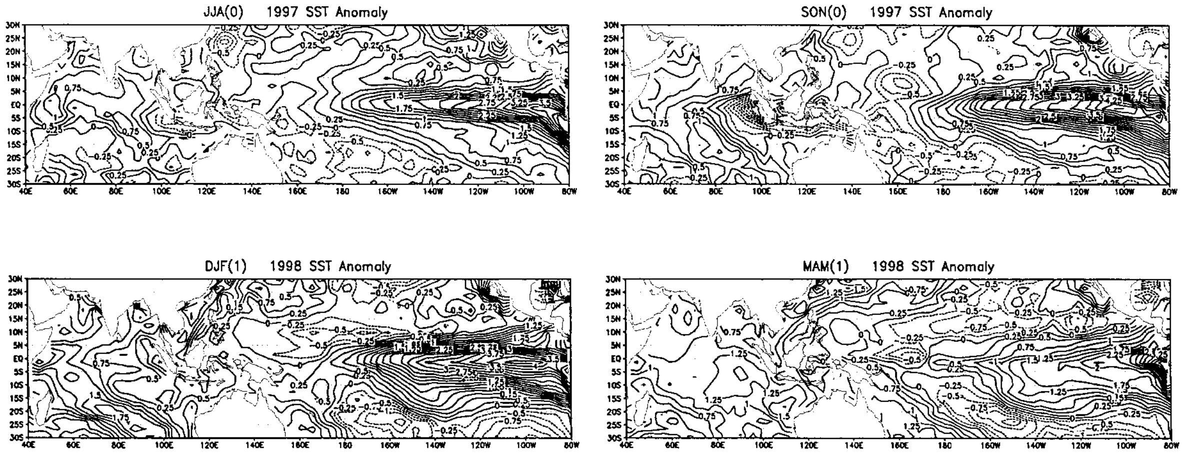

Fig. 3. Evolution of anomalous SST in the tropical Pacific and Indian Ocean during the 1997–98 El Niño episode.

mote SSTA affect from the tropical Atlantic and midlatitude oceans. Our results show that this remote affect is small.

For each experiment above, the model is integrated for 15 months, from June 1 of an El Niño developing year to August 31 the following year. For each of 12 El Niño episodes during 1950–1999, four experiments (i.e., Exp1, Exp2, Exp3, and Exp4) were carried out. A composite evolution pattern is finally derived, based on the 12 El Niño runs.

A special attention is paid to the 1997–98 El Niño event. In association with this event, abnormal SST condition occurred in the equatorial Indian Ocean, with a cold (warm) SSTA and suppressed (enhanced) convection appearing in the eastern (western) Indian Ocean (Fig. 3). This zonally asymmetric SST mode was referred to as the Indian Ocean dipole or zonal mode (Webster et al. 1999; Saji et al. 1999). We intend to examine how this Indian Ocean dipole competes with the El Niño to affect the monsoon. Five ensemble experiments were carried out for this special event.

4. Relative role of remote vs. local SSTA forcing

4.1 El Niño composite

First, we present simulation results from the 12 El Niño composite. Figure 4 shows the composite low-level wind anomaly fields in northern fall of the El Niño developing year. By comparing Exp2 and Exp4, one may conclude that the local SSTA is critical in initiating the anomalous anticyclone over WNP in SON(0). Comparing the wind patterns in Exp3 and Exp1, one may note that in addition to the local SSTA impact, the Indian Ocean SSTA has a remote affect on the circulation anomaly in the western Pacific, helping to set up the anomalous WNP anticyclone. This remote affect seems consistent with Watanabe and Jin (2002), who pointed out a significant contribution of the Indian Ocean SSTA on the establishment of the WNP anticyclone. After initiated in northern fall, the anomalous anticyclone in WNP is maintained by both local and remote SSTA forcing (figure not shown). The anomalous anticyclone in SIO in SON(0) is much stronger in Exp3 than in Exp1, suggesting that local air-sea interactions (Li et al. 2003) are essential to lead to its rapid intensification.

To qualitatively describe the relative role of the remote versus local SSTA forcing, we plot maps that consist of both the anomalous pattern correlation and the root mean square error (RMSE) for precipitation and wind (averaged for zonal and meridional components) fields over the western Pacific and Indian Ocean boxes, respectively. The pattern correlation and RMSE are calculated based on the reference experiment Exp4.

Figure 5 shows the pattern correlation and RMSE maps for the precipitation and wind anomaly for each season [from JJA(0) to JJA(1)]. From these maps, one may note that

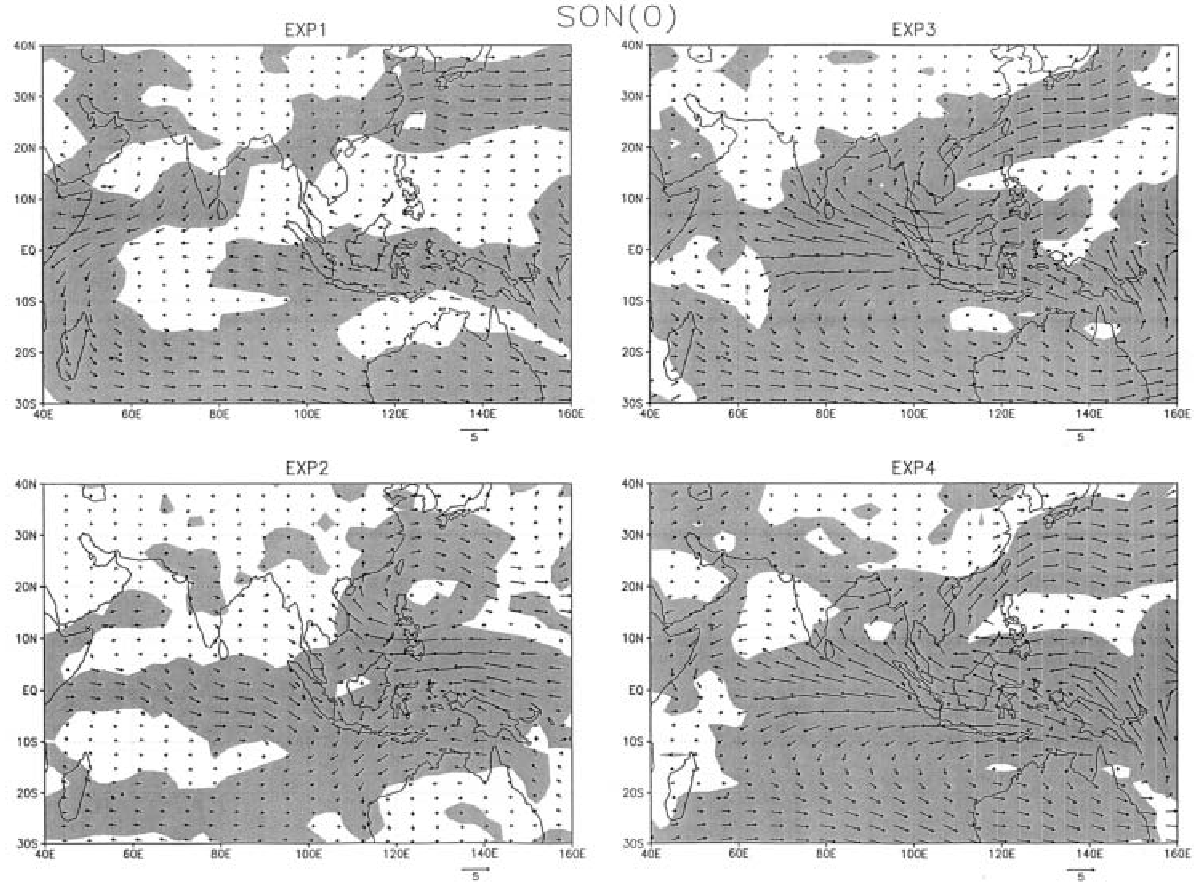

Fig. 4. 925 hPa wind anomaly patterns (unit: ms^{-1}) in northern fall of the El Niño developing year [SON(0)] for Exp1 (eastern Pacific SSTA forcing only), Exp2 (western Pacific SSTA forcing only), Exp3 (eastern Pacific plus Indian Ocean SSTA forcing) and Exp4 (combined eastern Pacific, western Pacific and Indian Ocean SSTA forcing). The patterns are based on 12 El Niño composite. The shading represents regions with 95% significance level or above.

the combined eastern Pacific and Indian Ocean forcing (Exp3, triangle) gives rise to reasonable (say, pattern correlations exceed 0.4) rainfall and wind patterns in the western Pacific (open) for all seasons, indicating the importance of the remote SSTA forcing. The local SSTA, on the other hand, is crucial in initiating the anomalous WNP anticyclone in northern fall, as clearly illustrated in both the precipitation and wind maps (see the open circle in Fig. 5). By comparing the correlation coefficients between Exp1 (open square) and Exp3 (open triangle), one may conclude that the Indian Ocean SSTA contributes to circulation anomalies in the western Pacific primarily during the El Niño developing phase [i.e., JJA(0) and SON(0)], but much less so during the El Niño mature and decaying phases.

The eastern Pacific SSTA exerts a great affect on anomalous winds over the tropical Indian Ocean during the peak phase of El Niño. In DJF the wind pattern correlation in presence of the remote eastern Pacific SSTA forcing alone (Exp1) is even greater than the combined Indian Ocean and eastern Pacific SSTA forcing (Exp3), opposite to the difference in the rainfall correlations. This implies that in the Indian Ocean the precipitation anomaly is to a large extent determined by local SSTA, whereas the wind anomaly is more determined by remote forcing from the eastern Pacific. In other seasons, however, anomalous winds in the Indian

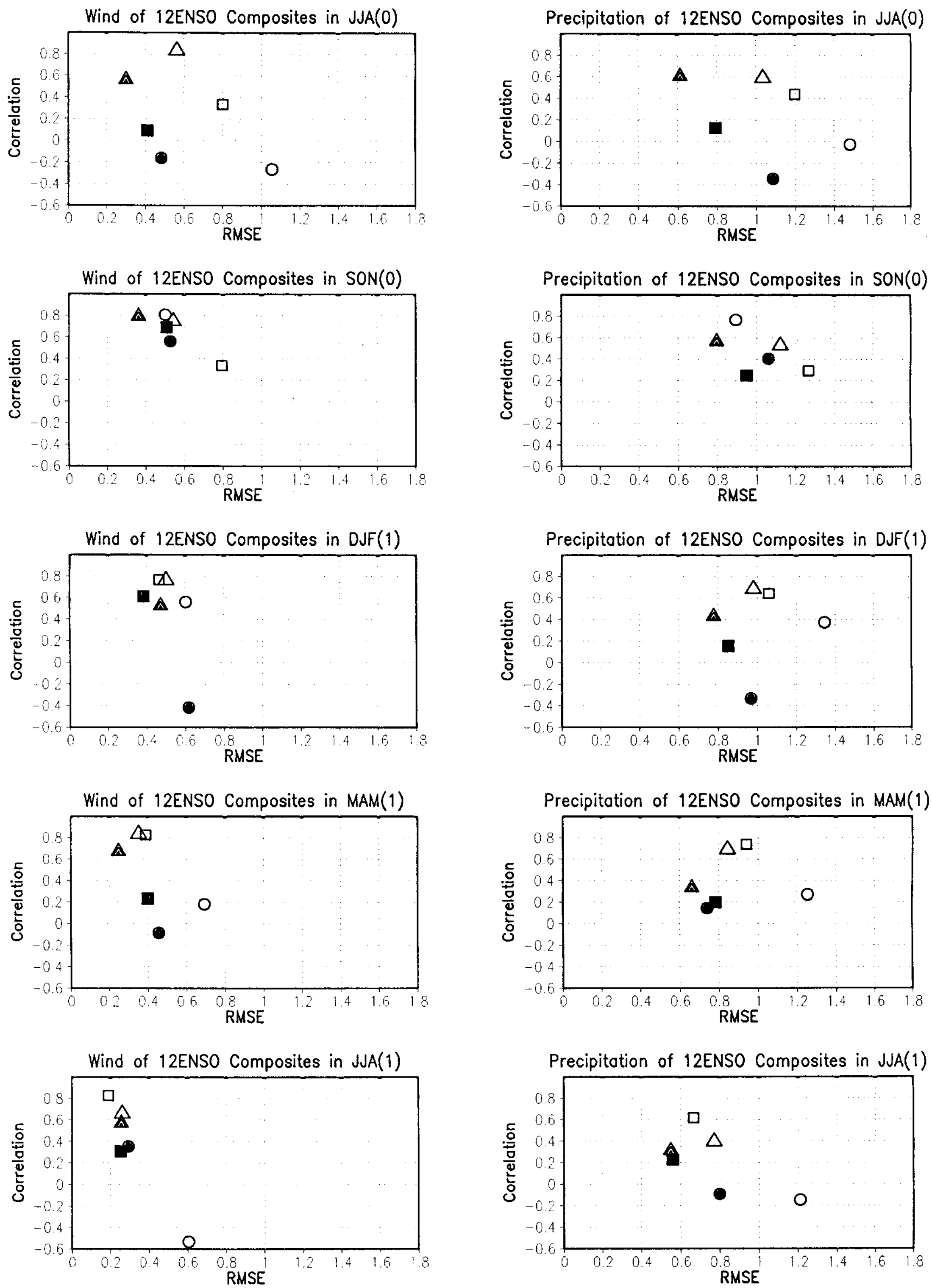

Fig. 5. Anomaly pattern correlation coefficients and root mean square errors at Exp1 (eastern Pacific SSTA forcing only, square), Exp2 (western Pacific SSTA forcing only, circle) and Exp3 (eastern Pacific plus Indian Ocean SSTA forcing, triangle) for the wind (left panels) and precipitation (right panels) fields in the tropical western Pacific domain (open) and the tropical Indian Ocean domain (close). The correlation and RMSE calculations are referenced to Exp4 (combined eastern Pacific, western Pacific and Indian Ocean SSTA forcing) based on the 12 El Niño composite.

Ocean are primarily driven by local SSTA forcing. During the El Niño mature phase (DJF), the rainfall pattern correlation in Exp1 (see the close square) is only about 0.2, which is significant lower than the wind counterpart (0.6). This implies that the ENSO indirectly affects rainfall fields in the Indian Ocean through the wind-induced SST changes (i.e., El Niño first remotely changes the wind and then changes the SST). With the fixed climatological SST in Exp1, the rainfall anomaly in the Indian Ocean does not significantly correlate to the ENSO. This points out the necessity to use a coupled air-sea model in the warm ocean to properly simulate/predict rainfall anomalies in response to remote El Niño forcing.

The numerical experiments above reveal a seasonal-dependent character of inter-basin teleconnection between the tropical Pacific and Indian Oceans, that is, the Indian Ocean SSTA exerts a remote affect on the western Pacific wind anomaly, primarily in northern summer and fall, during the El Niño developing year (as reflected by a large gap in correlation between open triangle and open square in Fig. 5), whereas the eastern Pacific SSTA has the greatest affect on the Indian Ocean circulation (the close square) during the mature phase of the El Niño (DJF). The western Pacific SSTA, on the other hand, has a modest affect on anomalous winds over the equatorial and southern Indian Ocean.

It is noted that the western Pacific SSTA forcing alone leads to local negative pattern correlations in both the rainfall and wind fields in El Niño developing and decaying summers [i.e., JJA(0) and JJA(1)]. This is consistent with AGCM inter-comparison results by Wang et al. (2004), who pointed out a clear negative correlation between the observed and AMIP-type model simulated rainfall anomalies over the monsoon regions. Again, this points out a need to apply a coupling approach, as the SSTA in the warm ocean is both a cause and a result of precipitation anomalies.

4.2 1997–98 El Niño case

Due to its exceptionally large amplitude, the El Niño in 1997–98 exerted a large affect on circulation anomalies over the Indian Ocean. To illustrate the relative role of remote and local SSTA, Figure 6 shows the simulations of the five-ensemble-mean wind anomaly patterns in Exp1 and Exp3, from the El Niño developing summer to winter. Similar wind patterns appear in both experiments, indicating that the significant part of the Indian Ocean circulation anomalies is attributed to remote El Niño forcing, consistent with several previous studies (e.g., Ueda and Matsumoto 2000; Tokinaga and Tanimoto 2004). The amplitude of the wind response, on the other hand, is greatly enhanced when both the remote and local SST anomalies are included (i.e., Exp3), suggesting the possible role of local air-sea interactions in enhancing the Indian Ocean climate variability (Saji et al. 1999; Li et al. 2003).

Anomalous wind patterns in the western Pacific bear many similarities between Exp1 and Exp4 in the El Niño developing summer and winter (figure not shown), suggesting that the local circulation anomalies during the seasons are primarily forced by the remote SSTA in the eastern Pacific. The local western Pacific SSTA, on the other hand, had two effects. First, it helped initiate the anomalous anticyclone over the WNP in SON 1997. Secondly, it helped maintain the anomalous circulation in the decaying phase of El Niño, particularly in JJA 1998 when the eastern Pacific SSTA had changed its phase from a warm to a cold anomaly.

The pattern correlation and RMSE maps indicate that both the remote forcing from the eastern Pacific and the local SSTA in the WNP played an important role in different phases of the El Niño development (see Fig. 7). For instance, the remote El Niño forcing is important for the establishment of both wind and precipitation anomalies in western Pacific in JJA(0) and DJF (see the open square), whereas the local forcing is important in SON(0), particularly in the precipitation field (the open circle). The local SSTA forcing becomes dominant in JJA(1) (the open circle), when the El Niño is diminishing. The Indian Ocean SSTA in 1997 seems to have a modest effect on wind anomalies over the western Pacific.

The primary factor that influences precipitation anomalies over the tropical Indian Ocean is the local SSTA, which can be inferred from the pattern correlation maps that there are large gaps between correlation coefficients in Exp3 and Exp1. Consistent with the 12 El Niño

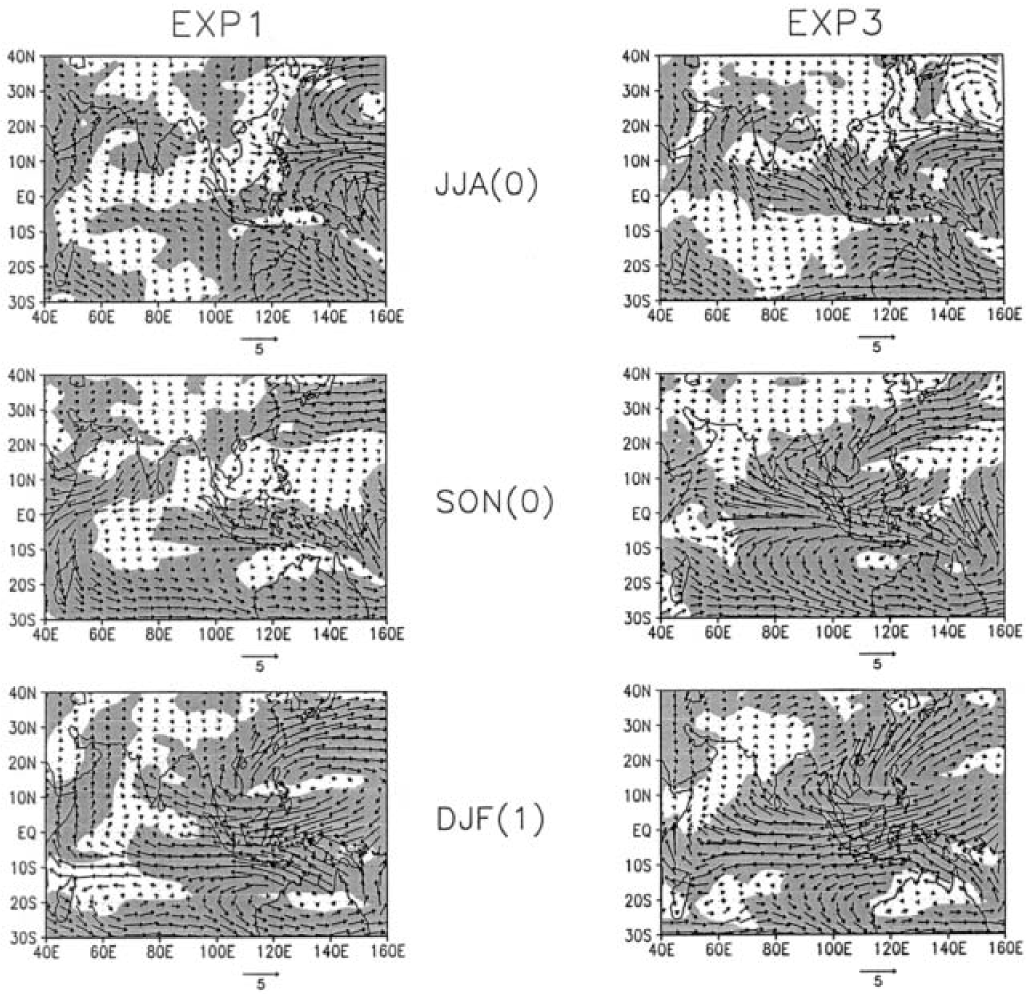

Fig. 6. 925 hPa wind anomaly patterns (unit: ms^{-1}) from JJA 1997 to DJF 1998 for Exp1 (eastern Pacific SSTA forcing only, left panels) and Exp3 (eastern Pacific plus Indian Ocean SSTA forcing, right panels) based on the five-ensemble average of the 1997–98 El Niño simulations. The shading represents regions with 95% significance level or above.

composite, the result above indicates that the rainfall anomalies over the Indian Ocean are primarily attributed to the local, not remote (eastern Pacific) SSTA forcing, while the wind anomalies are determined by both remote and local forcing. A strong Indian Ocean dipole event developed during the development phase of the 1997–98 El Niño (Saji et al. 1999; Ueda and Matsumoto 2000), and this SST dipole reached a peak phase in northern fall and then rapidly decayed. By the spring 1998 a basin-wide warming appeared. This dipole-to-basin mode transition is attributed to a seasonal-dependent thermodynamic air-sea feedback, and oceanic wave effects (Li et al. 2003). Note that the relative roles of the remote versus local forcing in inducing zonal and meridional wind anomalies are different. For instance, during the El Niño mature phase, the meridional wind component over the Indian Ocean is primarily driven by local SSTA, as inferred from the separation of correlation coefficients between Exp1 (close square) and Exp3 (close triangle) in Fig. 8 (right panel). The zonal wind component, on the other hand, is mainly attributed to the remote forcing from the eastern Pacific (the close square, left panel of Fig. 8). During the El Niño decaying phase, both the meridional and zonal

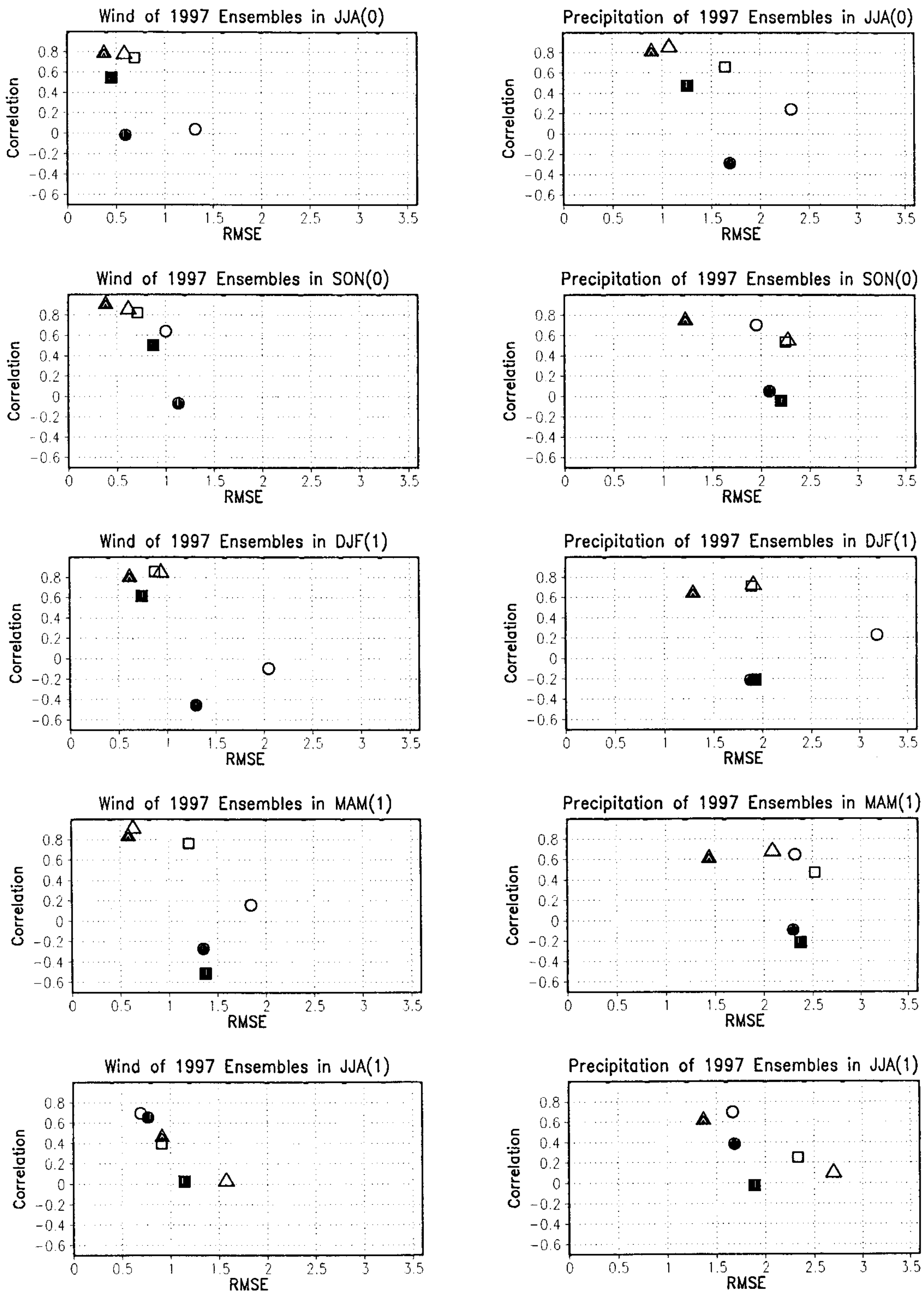

Fig. 7. Same as Fig. 5 except for the 5-ensemble average of the 1997–98 El Niño.

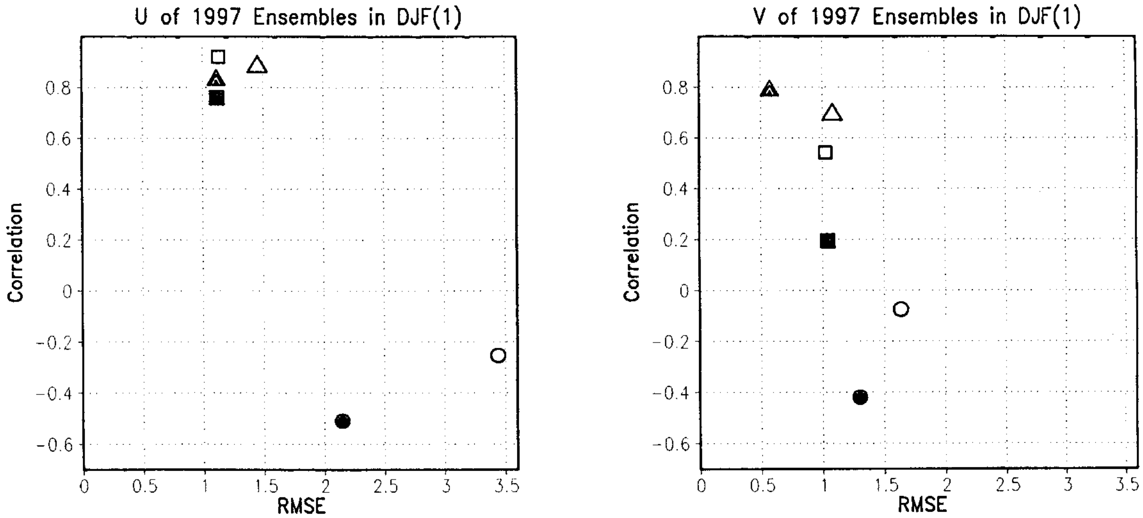

Fig. 8. Same as Fig. 7 except for zonal (left panel) and meridional (right panel) wind components in the mature phase of the 1997–98 El Niño.

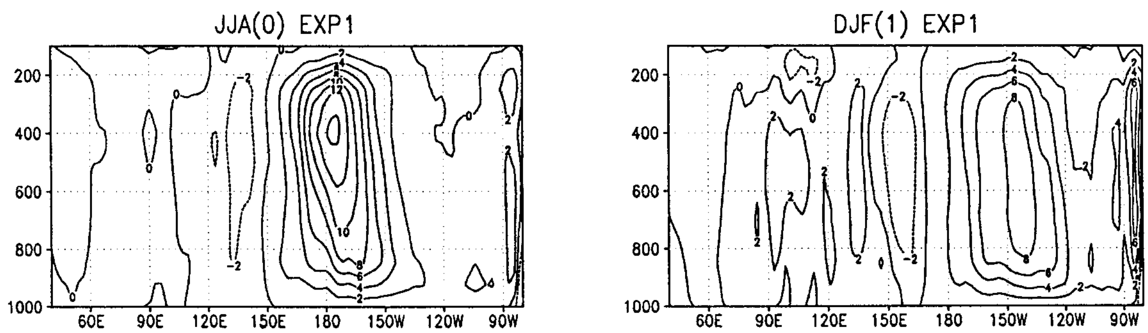

Fig. 9. Vertical-cross section of p-vertical velocity (unit: -0.01 Pa s^{-1}) averaged between 5°S and 5°N in JJA 1997 (left panel) and DJF 1998 (right panel). The results are from Exp1 (eastern Pacific SSTA forcing only) based on the five-ensemble average of the 1997–98 El Niño simulations. Positive (negative) values represent upward (downward) motion.

wind components are primarily driven by the local SSTA.

The seasonal dependence of the El Niño teleconnection may be discerned from the ascending/descending branches of Walker circulations across the equatorial Pacific and Indian Oceans. Figure 9 shows vertical velocity anomalies averaged at 5°S–5°N in JJA 1997, and DJF 1998 from simulations of Exp1. Although SSTA amplitude is greater in DJF, the associated upward motion in the central equatorial Pacific is stronger in JJA, simply because the summer maximum SSTA is located more to the west where the mean SST is higher. On the other hand, even with the stronger convection anomaly over the central equatorial Pacific in boreal summer, the response of anomalous equatorial Walker circulation is mainly confined to the east of 120°E, illustrating a single cell structure. This is remarkably different from the boreal winter when the equatorial atmospheric response extends farther to the Indian Ocean, leading to double Walker cells with one over the Pacific, and the other over the Indian Ocean, even though the convective forcing over the central equatorial Pacific is weaker. Physical mechanisms that give rise to the seasonal dependence of the El Niño teleconnection are unclear. It is speculated that it might be attributed to the annual cycle of basic-state convective activities over the maritime continents. In boreal summer as the thermal equator (represented by maximum SST and specific humidity) shifts significantly northward (say, to 15°N), convection over the maritime continent is largely reduced, and weak subsidence controls near and south of the equator. An enhanced subsidence due to El Niño forcing in this scenario does not significantly affect local heating anomalies. As a result, the Walker cell over the Indian Ocean is near normal. In boreal winter, on the other hand, maximum seasonal convection is located in the maritime continent/northern Australia. As a result, atmospheric heating over the maritime continent is quite sensitive to the remote El Niño forcing.

The western Pacific SSTA exerts a significant affect on the wind anomaly over the Indian Ocean in JJA 1998. The pattern correlation in this season is 0.4 for precipitation and 0.6 for the wind, indicating a potential teleconnection between the WNP summer monsoon, and the Indian Ocean during the decaying phase of the El Niño. As the WNP anticyclone persists, due to the thermodynamic air-sea feedback (Wang et al. 2000) from northern winter to the following summer, it leads to a weak WNP summer monsoon. The reduced heating along the WNP monsoon trough may induce anomalous southward cross-equatorial flows, and thus change the wind along the coast of Sumatra (Li et al. 2002).

5. Conclusion

The primary observational feature of the Asian-Australian monsoon anomaly associated with the El Niño teleconnection is the evolution of the anomalous anticyclones over the WNP and SIO. In this study, we investigate the relative role of remote and local SSTA forcing in generating the two anomalous anticyclones by conducting idealized GCM experiments. The analyses of both the composite El Niño, and special 1997–98 El Niño episode, show that the local SSTA plays an important role in initiating the anomalous WNP anticyclone in northern fall. The maintenance of the WNP anticyclone is attributed to both the remote and local SSTA forcing. The initiation of the anomalous anticyclone over the SIO is primarily attributed to local SSTA forcing, but in 1997 the remote forcing from the eastern Pacific also plays a role.

The numerical experiments reveal a seasonal dependence of the Pacific-Indian Ocean teleconnection. The Indian Ocean SSTA exerts a significant impact on circulation anomalies in the western Pacific during the El Niño developing summer and fall, but much less so in the subsequent seasons. The eastern Pacific SSTA exerts a greater impact on low-level wind anomalies over the Indian Ocean during the mature phase of the El Niño (boreal winter), even though the central Pacific heating associated with the El Niño forcing is stronger in boreal summer. It is speculated that this seasonal-dependent teleconnection is attributed to the annual cycle of convective activities over the maritime continent.

During the mature phase of 1997–98 El Niño, the meridional wind anomaly over the Indian Ocean is primarily driven by local SSTA forcing, while the zonal wind component is mainly forced by the remote SSTA in the eastern Pacific.

In this study the observed SST condition is specified as a boundary forcing, but in reality the SSTA in the warm oceans might be a result of the anomalous monsoon forcing (Wang et al. 2004). Therefore it might be inadequate to conduct AMIP-type experiments with fixed SST. This points out a need to conduct coupled model experiments, which allow active interactions between the monsoon and underlying oceans.

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