ENSO and Asian Summer Monsoon:
Persistence and Transitivity in the Seasonal March

By Borjiginte Ailikun and Tetsuzo Yasunari

Institute of Geoscience, University of Tsukuba, Tsukuba, Japan

Abstract

The lagged correlations between monthly Asian summer monsoon indices and El Niño-Southern Oscillation (ENSO) index change prominently in the middle of the summer season, based upon data from the late 1970's to late 1990's. Following this change in correlations, the traditional summer monsoon season (June–July–August–September) could be divided into two sub-periods in terms of the interannual variability. One is early summer (June), in which the variability of the Asian monsoon is strongly influenced by the anomalous state of ENSO in the previous winter. Another is mid-late summer (July–August–September), in which the Asian monsoon is related to the anomalous state of ENSO in the following winter rather than the previous winter.

The precursory signals of the anomalous Asian summer monsoon which are associated with the anomalous state of ENSO in previous seasons, are valid only for the variability of monsoon in the early summer, but not for that in the whole summer season. Therefore, the drastic change of persistence of the ENSO/monsoon system occurs after the early summer, and a new anomalous state tends to start from the middle or late summer. In this coupled system of ENSO and monsoon, the role of the western Pacific seems to be much different from the eastern Pacific. The anomalous state of sea surface temperature (SST) over the western Pacific warm pool area tends to persist from winter until the following late spring (May), and the related abnormal convective activity over that region can be maintained until the following early summer (June). Such kind of characteristics of persistence over the western Pacific is likely to have a memory effect of the anomalous ENSO state, and plays an active role in influencing the variability of the Asian monsoon in the following early summer.

1. Introduction

The relationships between the interannual variability of the Asian summer monsoon and El Niño-Southern Oscillation (hereafter ENSO) have been studied extensively by many researchers (e.g., Shukla and Paolino 1983; Mooley and Shukla 1987; Yasunari 1990). The weak (strong) Asian summer monsoon is often related to the El Niño (La Niña) event over the tropical Pacific in the following winter, indicating that the variability of the Asian summer monsoon plays an active rather than passive role in determining the tropical ENSO events.

Corresponding author: Tetsuzo Yasunari, Institute of Geoscience, University of Tsukuba, 1-1-1 Tennoudai, Tsukuba 305-8571, Japan.
E-mail: yasunari@atm.geo.tsukuba.ac.jp

In many studies before the 1990's, the all-Indian monsoon rainfall index (hereafter IMR) was widely used to represent the intensity of the Asian summer monsoon. The IMR data set based on the observations from land-based rain gauge data (Parthasarathy et al. 1992; 1995), has been proved to be a useful index to evaluate the importance of the Indian monsoon as well as the Asian monsoon.

On the other hand, Webster and Yang (1992) defined another type of monsoon circulation index using the objectively analyzed wind data products from the European Centre for Medium-range Weather Forecasts (ECMWF) and the National Meteorological Center (NMC, now called the National Center for Environmental Prediction, NCEP). They used the vertical zonal wind shear (hereafter US) between lower (850 hPa) and upper (200 hPa)

troposphere over south Asia (5°–20°N, 40°–110°E). This US index was expected to represent a broad-scale baroclinity between the Asian continent and Indian Ocean associated with the intensity of the Asian summer monsoon. Goswami et al. (1999) pointed out that the seasonal mean US has insignificant correlation with the IMR, which suggests the other processes may also contribute to the US index. Ailikun and Yasunari (1998) noted that the intensity of the US index is strongly associated with convective activity over the western Pacific warm pool area.

Associated with the relationships between ENSO and Asian summer monsoon in the interannual variability, the persistence of the ENSO/monsoon system in the seasonal cycle has been another important issue. Many general circulation models (GCMs), have suffered from bad forecasts in the northern spring months of March–May, which is called the "predictability barrier" (e.g., Latif and Graham 1991). This spring barrier also involves a similar drop off of persistence in central Pacific precipitation, eastern Pacific sea surface temperature (SST), southern oscillation index (SOI) and other ENSO indices (e.g., Wright 1979; 1985). Torrence and Webster (1998) presumed the phase locking of ENSO to the annual cycle, which causes this spring predictability barrier. Meanwhile, the anomalous state of the ENSO/monsoon system is likely to persist even through the spring "predictability barrier" of the ENSO (Webster and Yang 1992); e.g., the upper tropospheric zonal wind over south Asia was noted to maintain the same anomalous state from the previous winter to the summer monsoon season. Yang et al. (1996) pointed out that the precursory signals of the Asian summer monsoon are associated with the anomalous state of tropical SST and convection in the previous winter. Kawamura (1998) defined the meridional thickness index (hereafter MT) using the meridional difference in area-averaged upper-tropospheric (500–200 hPa) thickness between the northern Indian Ocean (0°–20°N, 50°–100°E) and the Tibetan Plateau region (20°–40°N, 50°–100°E). Remarkable anomalies in tropical SST and atmospheric circulation are also found to be related to the MT index.

Among these monsoon indices, the IMR is noted to be associated with the ENSO in the following winter, but US and MT are found to be related to that in the previous winter. Why are the relationships with ENSO so different by using different monsoon indices? If the precursory signals of Asian

summer monsoon could be found from the previous winter, how does the ENSO/monsoon system behave through the seasonal cycle, especially during the spring barrier? What is the dynamics of the change and/or persistence of the anomalous state? In this study, we will re-examine these issues based on the data 1979–97 to reveal the characteristics of the coupled ENSO/monsoon system, in terms of its seasonal cycle and interannual variability.

2.   Data and method

The monthly atmospheric circulation data (2.5° × 2.5° grid) obtained from the NCEP/NCAR (National Center for Atmosphere Research) reanalysis project (see details in Kalnay et al. 1996) is used. The monthly precipitation data of Climate Prediction Center Merged Analysis of Precipitation (CMAP) was adopted from January 1979 to December 1997, constructed by Xie and Arkin (1996; 1997) as part of the Global Precipitation Climatology Project (GPCP). This precipitation data set is based on the rain gauge data and satellite-derived precipitation estimates. The monthly outgoing longwave radiation data (OLR, 2.5° × 2.5° grid) was observed from the NOAA (National Oceanic and Atmospheric Administration) satellite for the period 1979–97. The monthly SST data set (2.0° × 2.0° grid) compiled by the Japan Meteorological Agency (JMA) was used. The area-mean monthly western Pacific (5°N–15°N, 120°–150°E) SST is calculated from this JMA data set.

The monthly Nino–3 index, which is the area-mean SST over the equatorial eastern Pacific (5°S–5°N, 150°–90°W), is adopted from the Climate Prediction Center (CPC). The monthly all-Indian monsoon rainfall index (IMR) constructed for the years 1817–1995, is adopted from Sontakke (1996). This IMR data is almost the same as those arranged by Parthasarathy et al. (1992; 1995) except with longer year coverage.

3.   Interannual variability of ENSO and asian summer monsoon

As reviewed in the introduction, the interannual variability of the Asian monsoon has different relationships with the tropical atmosphere/ocean system of ENSO through analyzing different types of monsoon indices (e.g., IMR and US). To exhibit it more clearly, the lagged correlations of each monsoon index in summer (June–July–August–September, hereafter JJAS) with the Nino–3 SST in the preceding/following months are plotted in
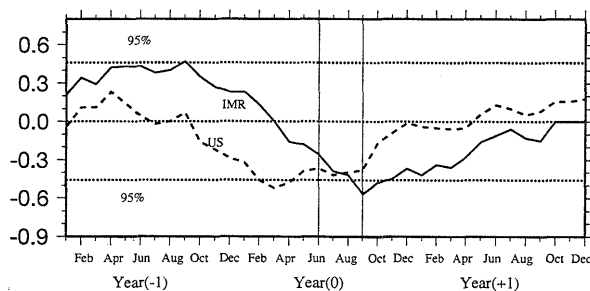
Fig. 1. Lagged correlations between Asian monsoon indices in season mean of summer (JJAS) and Nino-3 SST in the preceding/following months 1978–96. IMR is the solid line, US is the dotted line, 95% means the confidence level.

Fig. 1. The significant negative correlations of the US index (dotted line) with the Nino–3 SST appear in the previous winter and spring (February–April), implying that the weak (strong) vertical zonal wind shear over south Asia is associated with the El Niño (La Niña) event in the previous seasons. In contrast, the remarkable negative correlations of the IMR index (solid line) with the Nino–3 SST occur in late summer and early autumn (August-October), suggesting the weak (strong) Indian monsoon rainfall is associated with an (a) El Niño (La Niña) event in the following seasons. In Fig. 1, the interannual variability of IMR index shows a feature of quasi-biennial oscillation with the reversal of correlations between Year(−1) and Year(0), but US does not.

Table 1 gives the correlation coefficients between IMR and US in the seasonal mean (JJAS) and each month of summer (1977–95). Although the IMR and US are correlated well to each other in seasonal mean (0.59), it is mainly due to the high correlations in June (0.63) and September (0.79), and they have little relations with each other in July (0.45) and August (0.31). In Goswami et al. (1999), the

Table 1. The simultaneous correlation coefficients between IMR and US indices in seasonal and monthly mean 1977–95. Values with under-bars have exceeded the 95% confidence level.

JJAS	June	July	August	September
0.59	0.63	0.45	0.31	0.79

correlation coefficient between US (using NCEP reanalysis data set) and IMR (Parthasarathy's data set) is just 0.35. The difference of correlation here (0.59) from that in Goswami et al. (1999) may be due to the data set, however, the correlation coefficient of JJAS IMR between Parthasarathy's data and Santakke's data is 0.95 (1977–95).

In spite of the high correlation in the seasonal mean, the IMR and US have different relationships with ENSO as shown in Fig. 1. To investigate this feature more precisely, the lagged correlations between the monsoon indices in each month of summer and the Nino–3 SST in the preceding/succeeding months are computed as shown in Fig. 2. The weighted running mean monthly indices, calculated with a 1–2–1 nominal filter, were used to remove the influence of intraseasonal variability. However, for June and September, the original IMR was used because the rainfall in May or October over the Indian subcontinent is very small compared with that in each month of JJAS.

In June (Fig. 2a), the correlation patterns for IMR (solid line) and US (dotted line) are very similar to each other, i.e., they are both negatively correlated to the Nino–3 SST in the previous winter and spring. The US index is more significant (exceeding the 99% confidence level) than the IMR. This correlation pattern of the US in June is similar to that for JJAS US shown in Fig. 1. In July (Fig. 2b), unlike June, the IMR (solid line) is negatively correlated to the Nino–3 SST in late summer and the following autumn. The IMR in August (Fig. 2c) is negatively correlated to Nino–3 SST in the following seasons and positively correlated to that in the previous seasons, showing the characteristic of biennial oscillation in the (IMR) monsoon/ENSO system. From middle summer (July), correlations between monthly IMR and ENSO show nearly the same features as those of the seasonal mean (see Fig. 1). Though remarkable negative correlations appear between the July US and the Nino–3 SST in the previous winter months (Fig. 2b, dotted line), no significant correlations are found for the August US (Fig. 2c, dotted line). In September (Fig. 2d), the significant negative correlations are noticed both for the IMR (solid line) and US (dotted line) with the Nino–3 SST in the following autumn and winter. The relationships with ENSO both for IMR and US are nearly the same in September, which are very similar to the JJAS IMR.
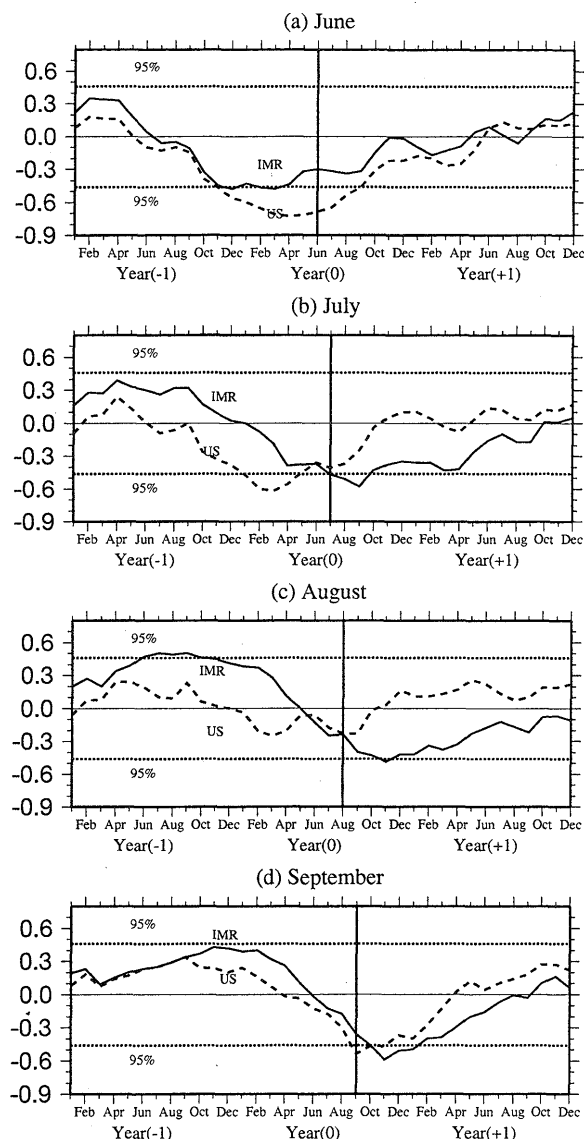
It is distinctly seen (for both IMR and US) that,

Fig. 2. Lagged correlations between monsoon indices in (a) June, (b) July, (c) August, (d) September, and Nino-3 SST in the preceding/following months 1978–96. IMR is the solid line, US is the dotted line, 95% means the confidence level.

the correlation pattern with ENSO in September (Fig. 2d) shows a systematic transition comparing with that in June (Fig. 2a). The critical change of the physical processes in the interaction between ENSO and the Asian monsoon is suggested to occur after the early summer. Thus, in terms of the interannual variability, the Asian summer monsoon season should be divided into at least two

sub-periods, which include June and September respectively. We also recognize that the relationship between ENSO and seasonal mean (JJAS) US is mainly attributed to that in June-July, but JJAS IMR is mainly attributed to that in July–August–September (hereafter JAS).

4. Variations of atmosphere-ocean system related to the seasonal march of the asian monsoon

The interannual variability of the Asian monsoon has been found to behave differently in different sub-periods of summer. Although the July US still has some similar features to that in June, the July IMR shows completely different characteristics comparing to that of June. Here, we divide the summer monsoon season into two sub-periods: early summer and mid-late summer. The early summer includes June, while the mid-late summer corresponds to July–August–September (JAS).

Figure 3 shows the composites of differences of precipitation from the previous late winter (January–February) to the following early winter (November–December) in terms of the significant strong and weak IMR in early and mid-late summer. These composites are made for positive anomaly years (1980, 1984, 1989, 1991, 1994) by subtracting the negative anomaly years (1982, 1983, 1987, 1992, 1995) of June (Fig. 3a–I to 3a–VI), and for positive years (1983, 1988, 1990, 1994, 1995) by subtracting the negative (1979, 1985, 1986, 1987, 1991) years of JAS (Fig. 3b–I to 3b–VI).

When the June IMR is above normal, the positive precipitation anomalies are distributed over the eastern Indian Ocean and a wide area of the western Pacific in previous JF (Fig. 3a–I), while the negative anomalies occur over the central and eastern Pacific. This see-saw pattern of precipitation anomalies over the central-eastern and western Pacific indicates that the strong Asian monsoon in early summer (June) is associated with the La Niña-like event in the previous winter. The anomalies over the eastern Indian Ocean are likely to be part of the westward extension of convection over the maritime continent. In the following spring (MA, Fig. 3a–II), the La Niña-type distribution of precipitation anomalies over the tropical Pacific still persists, but a below-normal anomaly appears over the southern Indian Ocean. This negative convection anomaly over the Indian Ocean could be an impact of the La Niña event to the Indian Ocean through the anomalous east-west cir-
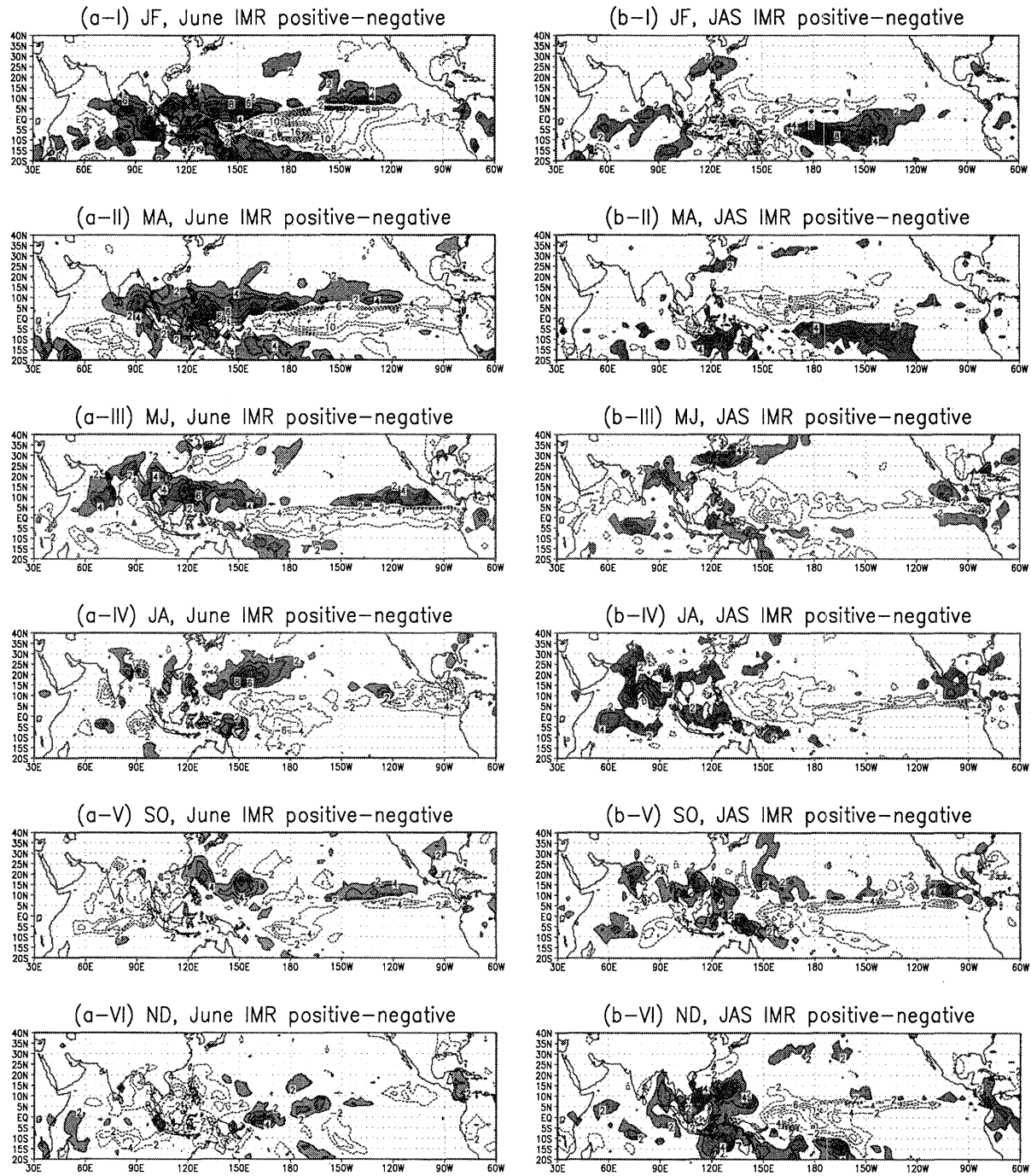
(a–I) JF, June IMR positive–negative

(b–I) JF, JAS IMR positive–negative

(a–II) MA, June IMR positive–negative

(b–II) MA, JAS IMR positive–negative

(a–III) MJ, June IMR positive–negative

(b–III) MJ, JAS IMR positive–negative

(a–IV) JA, June IMR positive–negative

(b–IV) JA, JAS IMR positive–negative

(a–V) SO, June IMR positive–negative

(b–V) SO, JAS IMR positive–negative

(a–VI) ND, June IMR positive–negative

(b–VI) ND, JAS IMR positive–negative

Fig. 3. The composite differences of precipitation (mm day^{-1}) from previous late winter to next early winter for years of postive and negative IMR anomalies in (a) June, and (b) JAS (Jul–Aug–Sep). (I). previous Jan–Feb, (II) previous Mar–Apr, (III) May–Jun, (IV) Jul–Aug, (V) following Sep–Oct, (VI) following Nov–Dec.

culation between western Pacific and the Indian Ocean. During the early summer (MJ, Fig. 3a–III), the positive anomalies over the eastern Indian Ocean and the tropical western Pacific appearing in previous seasons shift northward to the Asian monsoon and northwest of the western Pacific regions, while below normal precipitation anomalies remain over the southern Indian Ocean and the central Pacific. During the middle summer (JA, Fig. 3a–IV), the positive anomalies disappear from the Asian monsoon area, and the negative values begin to locate over some parts there. We thus could confirm that the Asian monsoon index in early summer (June) does not represent the convective activity over the south Asia for the mid-late summer (JAS).

From the following late summer to the post-monsoon period (SO, Fig. 3a–V), negative anomalies cover the wide area of the Indian Ocean and Asian monsoon region, and extend eastward to the maritime continent in the following early winter (ND, Fig. 3a–VI). Not as significant as that in the previous winter, the anomalous state of precipitation over the maritime continent and tropical western Pacific in the following winter (Fig. 3a–VI) tends to be out of phase to that in the previous winter (Fig. 3a–I), suggesting the biennial oscillation of the Asian monsoon. From Fig. 3a–I to 3a–VI, it is obvious that the activity of the Asian monsoon in early summer is more closely related to the anomalous state of tropical convective activity in the previous winter than that in the succeeding winter, and the prominent change of the anomalous state of precipitation is likely to occur between the early and late summer. It should be noted here that the distributions of anomalous precipitation associated with the extreme June US anomalies are entirely the same as the June IMR shown in Fig. 3a (not shown).

When the IMR anomaly in mid-late summer (JAS) is chosen as a reference, the seasonal march of anomalous precipitation shows a contrastive difference. In the previous late winter (JF, Fig. 3b–I), the negative anomalies are distributed over the western Pacific and positive values over the central and eastern Pacific, and another positive area is seen at some parts of the Indian Ocean. The El Niño-like distribution of precipitation anomalies over the tropical Pacific lasts until the following spring (MA, Fig. 3b–II). However, in the following early summer (MJ, Fig. 3b–III), the positive anomalies appear over the northern Bay of Bengal. During the mid-summer (JA, Fig. 3b–IV) the positive anomalies cover a wide area of south Asia and the maritime continent, and the negative anomalies spread over the central and eastern Pacific. Namely, the La Niña-like pattern is developed from mid-summer toward the following autumn (SO, Fig. 3b–V), with the positive anomalies over south Asia and the western Pacific, and negative anomalies over the central and eastern Pacific. In the following winter (ND, Fig. 3b–VI), the typical La Niña event occurs over the tropical Pacific. Therefore, the variability of the Asian monsoon in mid-late summer is associated with convective activity over the tropical Pacific in the following seasons, rather than that in the previous seasons.

Figure 4 shows the seasonal changes of SST anomalies composed in the same manner as Fig. 3. During the preceding winter (JF, Fig. 4a–I) of the strong June IMR, positive SST anomalies over the western-central Pacific and negative anomalies over the eastern Pacific are noticeable, which shows the characteristics of a La Niña event over the tropical Pacific. This La Niña-type distribution of SST anomalies lasts up to the following spring (MA, Fig. 4a–II) and early summer (MJ, Fig. 4a–III), but becomes indistinct in mid-summer (JA, Fig. 4a–IV). No remarkable SST anomalies are found in the succeeding autumn (SO, Fig. 4a–V) and winter (ND, Fig. 4a–VI). It should be noted, therefore, that the anomalies of the Asian monsoon as seen in IMR in early summer are associated with the anomalous state of tropical SST in the previous winter rather than that in the following winter.

In contrast, during the previous winter (JF, Fig. 4b–I) and spring (MA, Fig. 4b–II) of the strong JAS IMR, the remarkable positive SST anomalies appear over the central and eastern Pacific. This distribution of SST anomalies is nearly opposite to the case of strong June IMR (Fig. 4a–I and 4a–II). In early summer (MJ, Fig. 4b–III) the positive SST anomalies disappear and, in the mid-summer (JA, Fig. 4b–IV) a new see-saw pattern between the central/eastern Pacific (negative) and the northern Indian Ocean/western Pacific (positive) appears. This La Niña-like distribution of SST anomalies further develops in the following autumn (SO, Fig. 4b–V), leading to a remarkable La Niña phenomenon in the following winter (Fig. 4b–VI). Though this series of composite SST anomalies, in terms of the IMR variability in the mid-late summer, shows the characteristic of the biennial oscillation, the SST anomalies in the following seasons are more
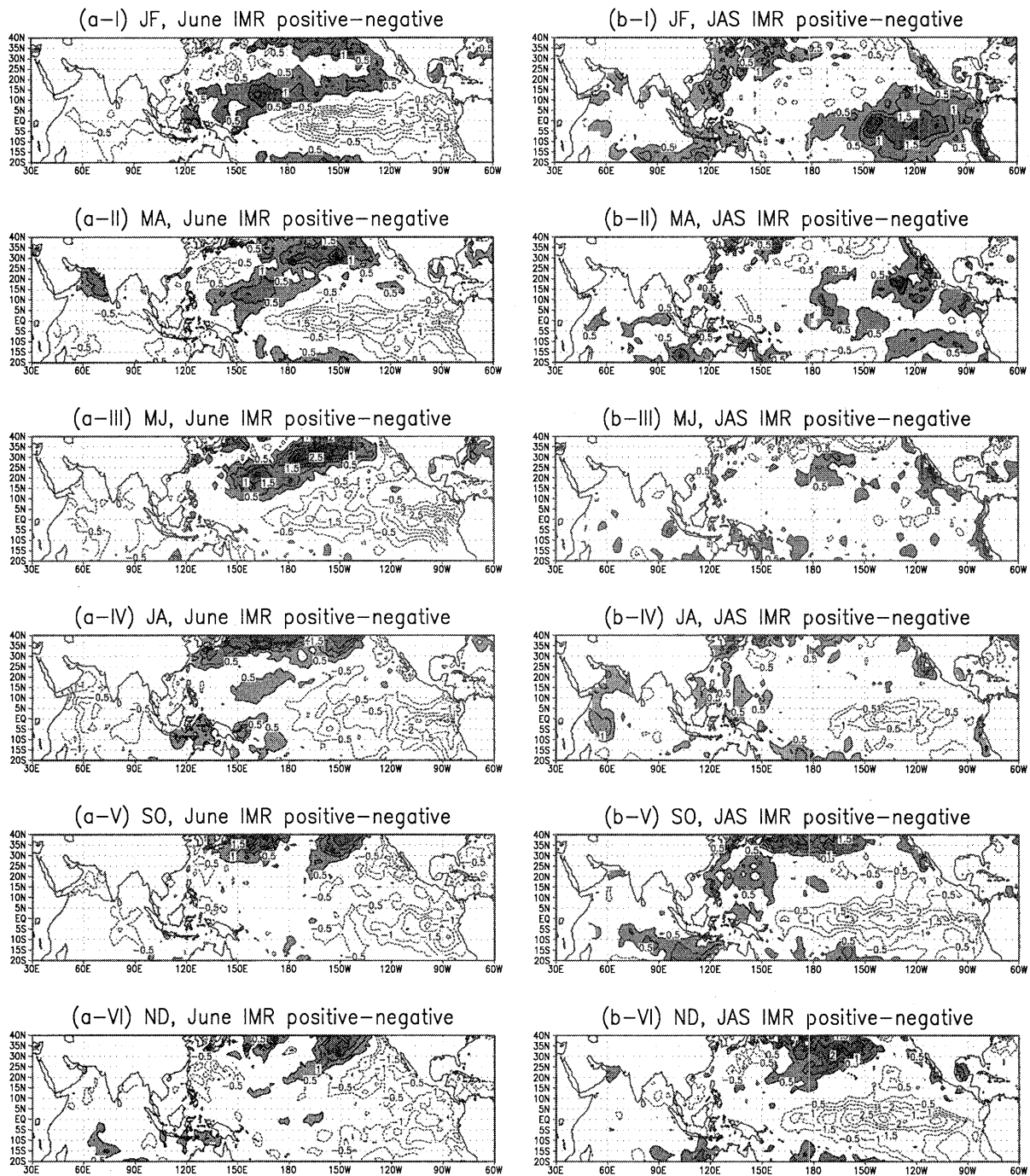
Fig. 4. Same as Fig. 3 except for the SST (℃).

prominent than those in the previous seasons. From two series of precipitation and SST composites, we could clearly see that the seasonal sequences of tropical convective activities and SST associated with the variability of the Asian monsoon are completely different between early and mid-late summer. In addition, the biennial oscillation associated with the Asian monsoon is noticed, particularly in the composites for the IMR in the mid-late summer.

We also notice that the distribution of precipitation in Fig. 3a–I (SST in Fig. 4a–I) is very similar to that in Fig. 3b–VI (Fig. 4b–VI), which suggests that the variability of the Asian monsoon in mid-late summer could possibly be related to that in the following early summer connected by the anomalous state of ENSO in the winter season. Although the lagged correlation coefficient between IMR in JAS and that in the following June is just 0.18, the IMR in September is well correlated to that in the next June. As plotted in Fig. 5, following the weak (strong) September such as 1982, 1986, 1991, 1994 (such as 1983, 1988, 1990, 1993), the IMR is significantly weak (strong) in next June. The lagged correlation coefficient between them is 0.51, which exceeds the 95% confidence level. Though the lagged correlation coefficient between IMR in September and US in the following June (0.45) has not exceeded the 95% confidence level, the weak (strong) September IMR years mentioned above are always followed by the same weak (strong) US in next June (figure not shown). This result may imply a cycle of the anomalous state of the ENSO/monsoon system that evolves from the mid-late summer and decays in the following early summer. The variability of the ENSO/monsoon system from mid-late summer to the next early summer will be discussed in the next section.
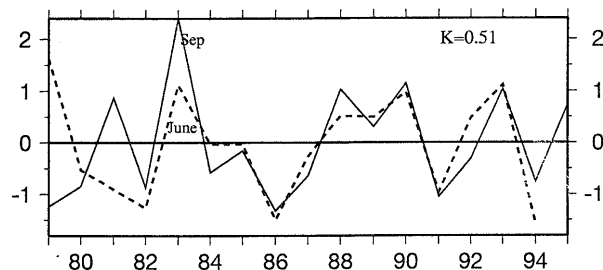

Fig. 5. Time series of IMR in September (solid line) and that in the following June (dotted line). K is the correlation coefficient between the two time series for 1979–94.

5. Persistence of the coupled ENSO/monsoon system

The precursory signals associated with the interannual variability of the Asian summer monsoon have been investigated in some previous papers (e.g., Webster and Yang 1992; Yang et al. 1996; Kawamura 1998). To examine the persistence of the precursory signals for the Asian summer monsoon, the auto-correlations of monthly zonal wind (u) over south Asia in the lower (850 hPa) and upper (200 hPa) troposphere from May to September (same area as US index) are shown
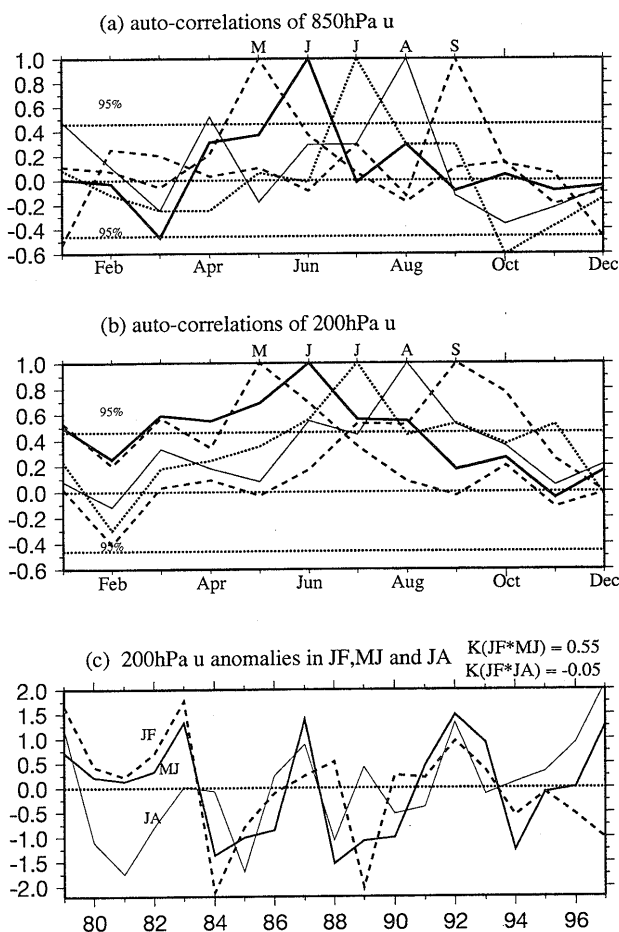

(a) auto-correlations of 850hPa u

(b) auto-correlations of 200hPa u

(c) 200hPa u anomalies in JF,MJ and JA   K(JF*MJ) = 0.55
                                          K(JF*JA) = -0.05

Fig. 6.   (a) Auto-correlations of monthly zonal wind at 850 hPa over south Asia (5°–20°N, 40°–110°E). (b) Same as (a) but for that at 200 hPa. (c) Time series of the anomalies of 200 hPa zonal wind over south Asia in JF (Jan–Feb, dotted line), MJ (May–Jun, thick solid line) and JA (Jul–Aug, thin solid line). K is the correlation coefficient 1979–97.

in Fig. 6. No significant lagged correlations are found between 850 hPa u in each month and that in the preceding/succeeding months (Fig. 6a). On the other hand, the remarkable lagged positive correlations exist between the 200 hPa u in May–June and those in the preceding winter/spring months (Fig. 6b). A striking feature is that the persistence of the 200 hPa u appears only from the previous winter up to the following early summer, not to the mid-late summer. Furthermore, the time series of anomalies of zonal wind at 200 hPa over south Asia in winter (JF, dotted line), early summer (MJ, thick solid line) and middle summer (JA, thin solid line) are plotted in Fig. 6c. The 200 hPa u in winter (JF) is well correlated with that in the following early summer (MJ) with the correlation coefficient of 0.55, but has no relation with that in the mid-late summer (JA, correlation coefficient is -0.05).

This remarkable change of persistence during the mid-late summer in the upper tropospheric zonal wind anomalies over south Asia implies that, the precursory signals of the Asian summer monsoon appearing in the previous winter/spring seasons are valid only for the early summer.

We now investigate the relationships with the ENSO of the precursory signals of the Asian monsoon in early summer. The composites of SST anomalies in winter (JF) for the anomalous 200 hPa zonal wind over south Asia are shown in Fig. 7. Five positive (1979, 1982, 1983, 1988, 1992) and negative (1984, 1985, 1989, 1994, 1996) cases from its anomalies are chosen for 1979–96. When the Asian 200 hPa u anomaly is positive (Fig. 7a) in JF, the El Niño-like see-saw pattern of SST anomalies are located over the eastern and western Pacific. The positive anomalies are also distributed over the
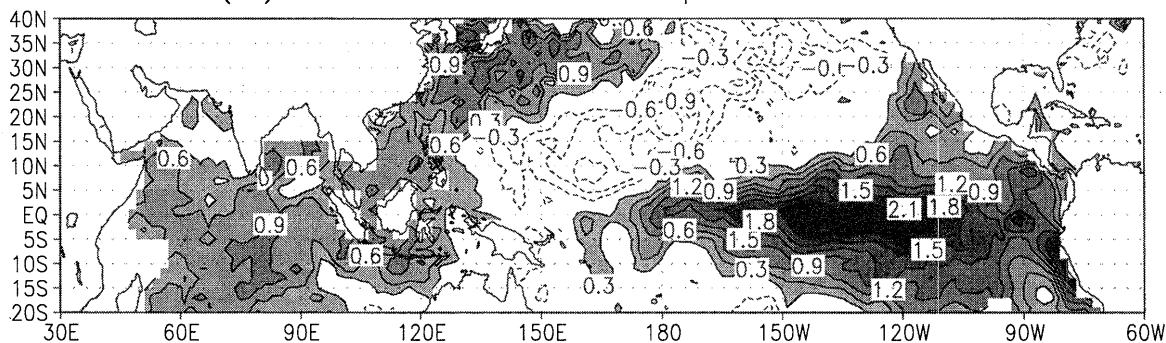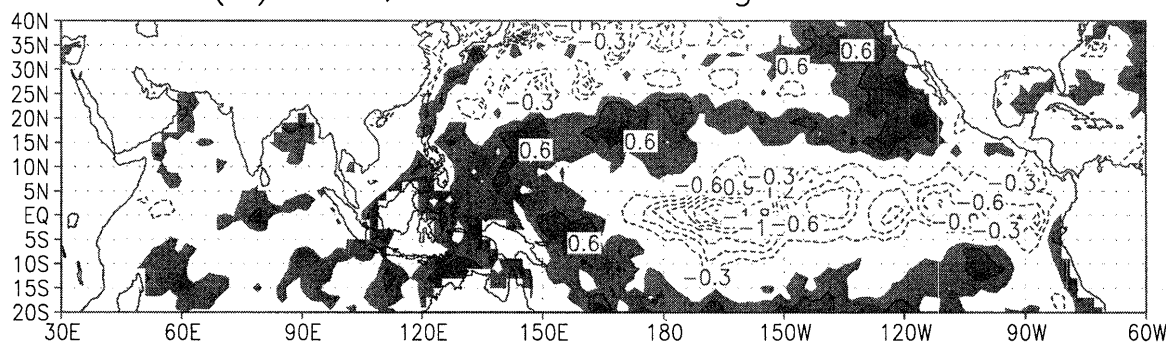

Fig. 7. The composites of the SST anomalies (°C) when the zonal wind anomalies at 200 hPa over south Asia are (a) positive, and (b) negative in winter (Jan–Feb).
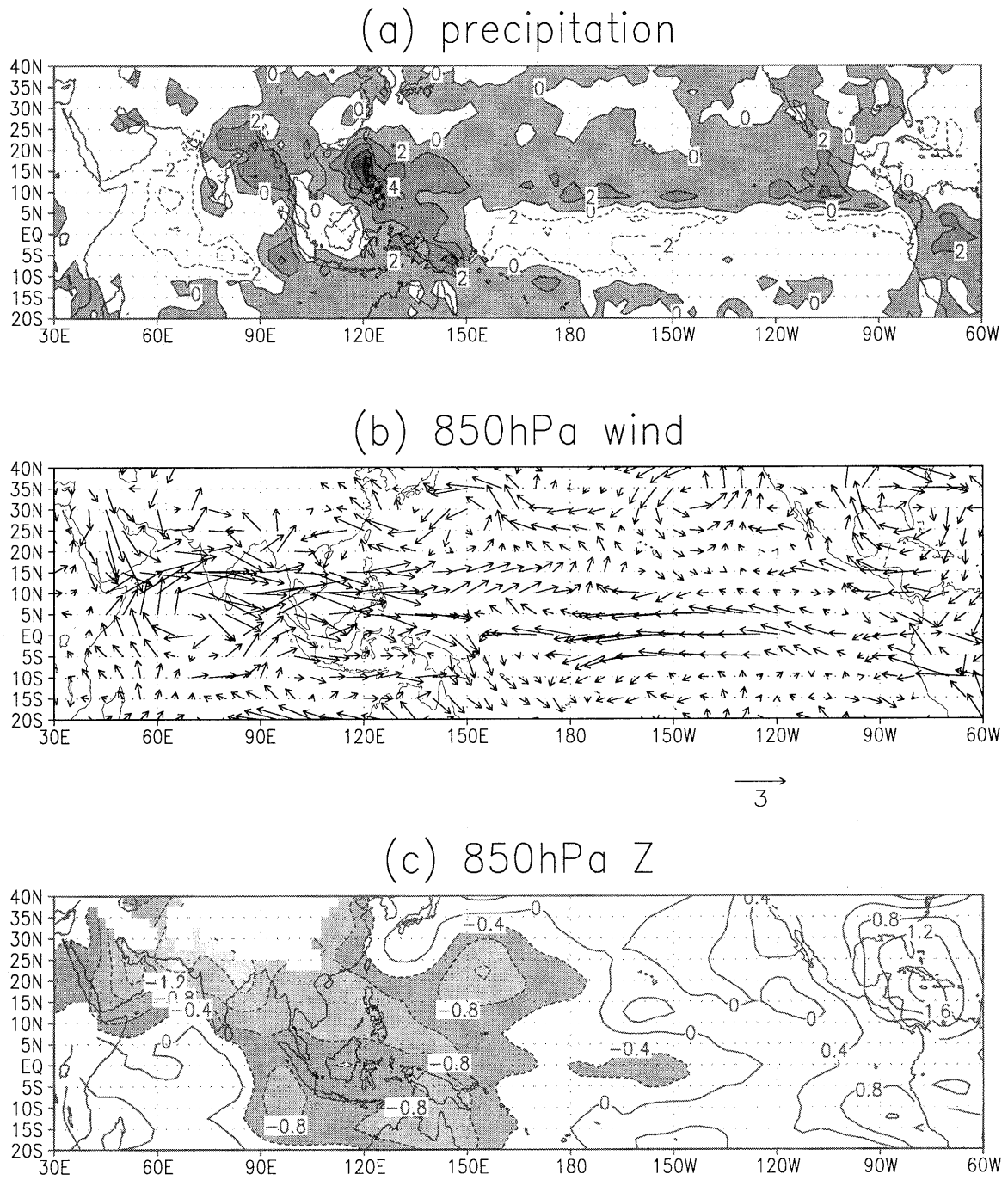
(a) precipitation

(b) 850hPa wind

(c) 850hPa Z

Fig. 8. The composites of differences of (a) precipitation (mm day^{-1}), (b) 850 hPa wind (m s^{-1}), and (c) normalized geopotential height at 850 hPa in June for years of positive and negative US anomalies.

Indian Ocean and mid-latitude northwest Pacific Ocean. By contrast, when the 200 hPa u anomaly is negative (Fig. 7b), the La Niña-like SST anomalies are spread over the tropical Pacific, i.e., reversal of the positive anomaly case. Here, we could recognize that, the anomalous pattern of the tropical SST corresponding to the anomalous u at 200 hPa as the monsoon precursory signal, it is very similar to that for the anomalous IMR of early summer shown in Fig. 4a–I. It seems that the large-scale ENSO response can result in an abnormal upper tropospheric zonal wind over south Asia in winter, which persists from winter until the following early summer.

As shown in Fig. 6, the precursory signals of the Asian summer monsoon in winter appear only at the upper troposphere (200 hPa), while no such feature has been found over the lower troposphere (850 hPa). But, in late spring or early summer (May–June), the 850 hPa u begins to be coupled with that over the 200 hPa. The correlation coefficient of zonal wind over south Asia between 200 hPa and 850 hPa is only -0.30 in April, but increases up to -0.81 in May, and -0.90 in June 1979–97. Figure 8 illustrates the anomalies of precipitation, wind and geopotential height (z) at 850hPa composed for the years of strong (1984, 1985, 1986, 1989, 1990, 1994) and negative (1979, 1983, 1987, 1992, 1996, 1997) US anomalies in June 1979–97. For the composites of precipitation (Fig. 8a), the area around the Philippines is a center of the positive anomalies, and the Indian subcontinent and the Bay of Bengal are covered by positive anomalies as well. The negative anomalies are dominant over the equatorial Indian Ocean and the equatorial central/eastern Pacific. The distribution of precipitation anomalies in Fig. 8a is similar to that in Fig. 3a–III, except the Indian Ocean region. The asymmetric mode of precipitation anomalies distributed over the north (positive) and south (negative) Indian Ocean can be seen in Fig. 3a–III, but only the negative anomalies in Fig. 8a cover the north Indian Ocean.

At the 850 hPa (Fig. 8b), the westerly prevails from the Arabian Sea through south Asia to the western Pacific. One cyclonic cell is located near the Philippines, and the anticyclonic circulation is dominated at the north Indian Ocean, corresponding to the positive and negative precipitation anomalies at these two areas, respectively. However, this kind of feature does not exist in the mid-late summer (figures not shown). Furthermore,

the simultaneous correlation between the US index and regional-mean precipitation over the western Pacific warm pool area (10°–20°N, 120°–150°E) is 0.64 in June, but falls to 0.33 in JAS. Namely, the variability of the Asian monsoon in terms of US index is related to the convective anomalies over the western Pacific only during early summer (June). For the 850 hPa geopotential height (Fig. 8c), the negative anomalies are located at south Asia, north of the western Pacific and the wide area of maritime continent and western Pacific. While the positive anomalies are distributed near, and around, the Gulf of Mexico and eastern Pacific. Contrary to the Indian Ocean, the heating condition related to the abnormal US over the Asian continent is under the same anomalous state with that over the western Pacific. This result implies that the interannual variability of Asian monsoon in early summer is not only associated with the heat contrast between south Asia and the Indian Ocean, but also related to the heating condition (or the convective activity) over the western Pacific.

To examine the relationships between the precursory monsoon signals and the persistence of the tropical atmosphere/ocean system, the autocorrelations of SST in the western Pacific warm pool area (5°–15°N, 120°–150°E) for each month of the year are shown in Fig. 9. A remarkable autocorrelation can be found up to May, where the high relations were only with the previous months. The western Pacific SST in June–July–August correlates to those neither in previous nor in following months. It is interesting to note that the SST in September begins to correlate with those in the following months significantly, but not with the previous months (particularly prior to June). According to the variability of SST over the western Pacific warm pool area, we propose a concept of "summer
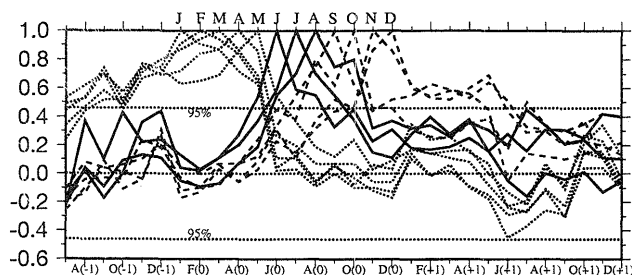

Fig. 9.   Auto-correlations of SST over the western Pacific warm pool area (5°–15°N, 120°–150°E) 1978–96.

persistence barrier" over the western Pacific to distinguish from the "spring persistence barrier" over the eastern Pacific. The summer persistence barrier suggests a process from the previous winter to the following May, and the persistence of SST is destroyed once the new summer monsoon season starts. After the summer persistence barrier, a new SST anomaly over the western Pacific tends to be rebuilt, showing significant lagged correlations with that in the following winter and spring.

The convective activity assciated with the persistence of SST over the western Pacific is investigated as well. The month-to-month variations of area-mean outgoing longwave radiation (OLR) over the western Pacific warm pool area composed for the years of high (1981, 1984, 1987, 1988, 1994) and low (1979, 1980, 1983, 1992, 1993) SST in May at the same region, are plotted in Fig. 10. The distinct difference of OLR between the two extremes can be seen from the previous winter until the following June and July. The difference of OLR in July is not as significant as that in June (under the 95% confidence level of student's t-test). It should be noted that, though the anomalous state of SST over the western Pacific warm pool area persists until the late spring (May), the anomalous convective activity can be continued until the early summer (June). Here, the western Pacific warm pool area is likely to memorize the signals of tropical ENSO system by persisting as the same anomalous state from the previous winter until the

OLR at western Pacific

Fig. 10. The month-to-month variations of OLR (W m^{-2}) averaged over the western Pacific warm pool area (5°–15°N, 120°–150°E) composed for years of high and low SST in May at the same region.

following June, and actively affect the variability of the Asian monsoon in the early summer.

6.　Summary and discussion

In this paper, we have studied the persistence and transitivity of the ENSO/monsoon system in the seasonal march through investigating the interannual variability of ENSO-related parameters (e.g., precipitation and SST) and Asian summer monsoon indices of IMR and US. By comparing the characteristics of interannual variability of Asian monsoon in early summer with that in late summer, we recognized that the relationships between ENSO and Asian monsoon show a systematic transition during the middle summer. The Asian monsoon season (JJAS) should be divided into two subperiods depending on the relationships with the atmosphere/ocean system in the tropical Pacific: one is the early summer (June), the other is the mid-late (JAS) summer. The variability of the Asian monsoon in early summer is associated with the anomalous state of ENSO in the previous winter, but the monsoon in mid-late summer is more related to the ENSO state in the following winter. The intensity of IMR in September is well correlated to that in the following June, which indicates a nearly one-year cycle of the anomalous state of the ENSO/monsoon system.

The precursory signals of zonal wind at 200 hPa for the anomalous Asian summer monsoon are found to be valid only for the early summer monsoon, but not for the whole monsoon season. This 200 hPa zonal wind, persisting from the previous winter to the early summer, is related to the anomalous state of ENSO in the previous winter season as well. On the other hand, the highest persistence of the western Pacific SST appears from winter until the following late spring (May), and decreases drastically by the summer monsoon season. Meanwhile, the anomalous state of convective activity over the western Pacific warm pool area can be maintained until the following early summer, i.e., June. The intensity of the Asian monsoon (IMR and US) in June appears to be closely associated with the convective activity over the western Pacific warm pool area which persisted from the previous winter to the early summer.

The concept of "monsoon year" for the coupled monsoon/atmosphere-ocean system (MAOS) was originally proposed in Yasunari (1991) and Yasunari and Seki (1992). This coupled ENSO/monsoon system tends to have an anomalous state starting in
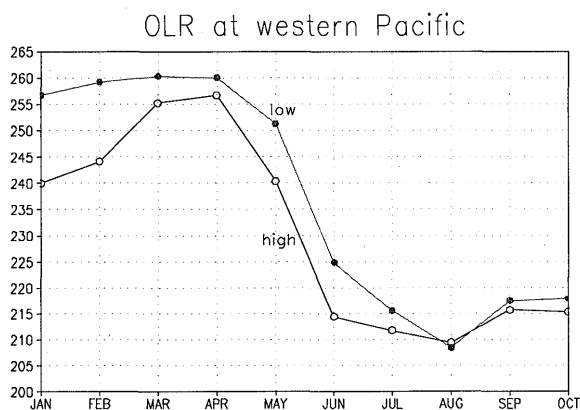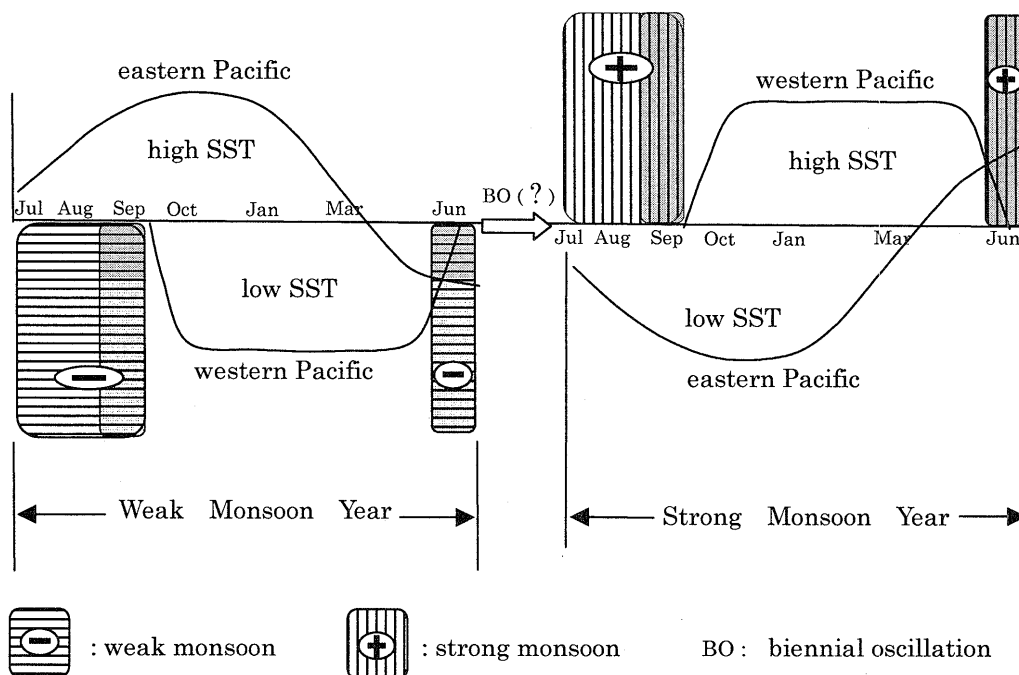
Fig. 11.   The schematic diagram of the two successive monsoon years for the coupled ENSO/monsoon system.

the northern summer monsoon season, and persisting for about one year. In this study, we have found that the relationships between the Asian monsoon and ENSO change radically during the summer season. Here, we propose a new conceptual model of monsoon year of the coupled ENSO/monsoon system as schematically shown in Fig. 11. This schematic diagram displays a time sequence of two successive monsoon years, which starts from the northern mid-late summer (JAS), and persists for about one year until the next early summer (June). The left part of the diagram shows the processes of the weak monsoon year, in which the Asian monsoon activity in the mid-late summer (JAS) is weak (shown with the horizontal lines) at the start of this one-year cycle. The tropical east-west circulation will be weakened by the influence of monsoon convective activity, which can lead to a warmer SST in the eastern Pacific and colder SST in the western Pacific in the following seasons, i.e., the El Niño-like condition. In this case, the negative anomalies of SST and convective activity at the western Pacific warm pool area may be crucial in maintaining the anomalous state of ENSO from winter until the next June, and actively leading to a weak Asian monsoon in the early summer. As an evidence of

this one-year cycle, the IMR in September is well correlated to that in the following June (area in shading). The right part of the diagram in Fig. 11 shows the processes of the strong monsoon year. The strong monsoon activity (shown with the vertical lines) in the mid-late summer could result in a La Niña event in the following winter. The La Niña signals, which are memorized in the western Pacific SST until the following early summer, could influence the variability of the Asian monsoon in a strong mode in June.

If the anomalous state of the Asian monsoon changes into the opposite phase during the middle summer, the weak (left) and strong (right) monsoon year can be manifested as a biennial oscillation (BO) of the ENSO/monsoon system. However, the correlation coefficient between June and JAS IMR is only 0.11 (0.28 between June and September), which indicates that the biennial oscillation of the ENSO/monsoon system was not remarkable during the period 1979–95. This may be due to some chaotic nature of the monsoon, possibly including the role of the land-surface anomalous forcing and the intra-seasonal variability. The mechanisms associated with the biennial oscillation for the ENSO/monsoon system will be discussed in

our following paper.

Also, we have noted that the importance of the western Pacific to the variability of the Asian summer monsoon. Traditionally, the Asian monsoon has been thought to be caused by the heat contrast between the Asian continent and Indian Ocean. In this study, the variability of the Asian monsoon in the early summer is found to be strongly related to the convective activity (or heating condition) at the western Pacific as well. As shown in Fig. 8, the anomalies of precipitation and 850 hPa z associated with the early summer monsoon are under the same anomalous state over south Asia and the western Pacific, which is contrastive to that over the Indian Ocean. In terms of the dynamical processes of how the convective activity over the western Pacific influences the early Asian summer monsoon, many possibilities can be proposed. Here, we presume two kinds of mechanisms. One is the direct influence mainly depending on the results in this study. At 850 hPa (Fig. 8b–c), based on the heat contrast between the Asian continent and Indian Ocean, the cyclonic circulation (low pressure) over the western Pacific seems to play an active role in intensifying the monsoon zonal wind at south Asia in the early summer. In other words, the anomalous state of the western Pacific SST and convective activity, which keeps the ENSO signals from the previous winter to the early summer, may influence the variability of Asian monsoon directly by enhancing (or reducing) the low-level monsoon westerlies and upper-level easterlies. This influence, however, exists only in the early summer, not for the whole summer season.

Another may be the indirect influence of the western Pacific proposed in Kawamura (1998), Kawamura et al. (1999) and Yang and Lau (1998). Kawamura pointed out the influence of ENSO on the land surface condition in central Asia via the Rossby-type response to the equatorially asymmetric mode of the convective activity over the Indian Ocean in spring. At the same time, the westward propagation of the equatorial Rossby wave forced by the anomalous convection at the western Pacific may be the necessary condition in generating the abnormal convective activity over the Indian Ocean. Although Yang and Lau (1998) pointed out the influence of the tropical SST on the ground wetness of the Asian continent, its relation with ENSO is not very clear. However, we have emphasized the direct influence of the western Pacific and Kawamura stressed the Rossby-response

to the convective activity over the Indian Ocean, undoubtedly, the influence from the northern mid-high latitude system on the monsoon activity (e.g., on the soil moisture condition of the Asian continent) is also very important. Furthermore, as noted by Yasunari and Seki (1992), the influences of the mid-high latitude atmospheric circulation and land-surface processes over the Eurasian continent from autumn to the next spring induced by the tropical ENSO system, are other problems to be investigated in the future.

Finally, we would like to stress that the results related to the persistence and transitivity of the ENSO/monsoon system shown in this study are based upon the data from the late 1970's to late 1990's. It should be noted that the interannual variability of ENSO and Asian monsoon could be modulated by the interdecadal changes (e.g., Torrence and Webster 1999; Wang 1995). How the variability of the ENSO/monsoon system is related to the interdecadal changes should be a future study.

References

Ailikun, B. and T. Yasunari, 1998: On the two indices of Asian summer monsoon variability and their implications. *Proceedings of International conference on monsoon and hydrologic cycle*, 222–224, Kyongju, Korea.

Goswami, B., V. Krishnamuthy and H. Annamala, 1999: A broad-scale circulation index for the interannual variability of the Indian summer monsoon. *Quart. J. Roy. Meteor. Soc.*, **125**, 611–633.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne and D. Joseph, 1996: The NCEP/NCAR 40 year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.

Kawamura, R., 1998: A possible mechanism of the Asian summer monsoon-ENSO coupling. *J. Meteor. Soc. Japan*, **76**, 1009–1027.

———, T. Matsuura and S. Iizuka, 1999: Role of an equatorial asymmetric mode in the Indian Ocean in the Asian summer monsoon-ENSO coupling. (submitted to *J. Geophys. Res*).

Latif, M. and N.E. Graham, 1991: How much predictive skill is contained in the thermal structure of an OGCM? *TOGA Notes*, **2**, 6–8.

Mooley, D. and J. Shukla, 1987: Variability and forecasting of the summer monsoon rainfall over India. C.P. Chang and T.N. Krishnamurti, Eds., *Monsoon Meteorology*, 26–59, Oxford Univ. Press.

Parthasarathy, B., R. Kumar and D. Kothawale, 1992: Indian summer monsoon rainfall indices. *Meteorol. Mag.*, **121**, 1871–1990.

———, A. Munot and D. Kothawale, 1995: Monthly and seasonal rainfall series for all India, homogeneous regions and meteorological subdivisions: 1871–1994. *Indian Institute of Tropical meteorology Research Report*, No.RR–065.

Shukla, J. and D. Paolino, 1983: The southern oscillation and long-range forecasting of summer monsoon rainfall over India. *Mon. Wea. Rev.*, **111**, 1830–1837.

Sontakke, N., 1996: *Study of climatic variations and climate monitoring over India and neighborhood.* PhD thesis, Indian Institute of Tropical Meteorology, India.

Torrence, C. and P. Webster, 1998: The annual cycle of persistence in the El Niño/Southern Oscillation. *Quart. J. Roy. Meteor. Soc.*, **124**, 1985–2004.

——— and P. Webster, 1999: Interdecadal changes in the ENSO-monsoon system. *J. Climate*, **12**, 2679–2690.

Wang, B., 1995: Interdecadal changes in El Niño onset in the last four decades. *J. Climate*, **8**, 267–285.

Webster, P. and S. Yang, 1992: Monsoon and ENSO: Selectively interactive systems. *Quart. J. Roy. Meteor. Soc.*, **118**, 877–926.

Wright, P., 1979: Persistence of rainfall anomalies in the central Pacific. *Nature*, **277**, 371–374.

———, 1985: The southern oscillation: An ocean-atmosphere feedback system? *Bull. Amer. Meteor. Soc.*, **66**, 398–412.

Xie, P. and P. Arkin, 1996: Analyses of global monthly precipitation using gauge observations, satellite estimates and numerical model predictions. *J. Climate*, **9**, 840–858.

——— and P. Arkin, 1997: Global precipitation: A 17 years monthly analysis based on gauge observations, satellite estimates and numerical model outputs. *Bull. Amer. Meteor. Soc.*, **78**, 2539–2558.

Yang, S. and K. Lau, 1998: Influence of the sea surface temperature and ground wetness on Asian summer monsoon. *J. Climate*, **11**, 3230–3246.

———, K. Lau and M. Sankar-Rao, 1996: Precursory signals associated with the interannual variability of the Asian summer monsoon. *J. Climate*, **9**, 949–964.

Yasunari, T., 1990: Impact of Indian monsoon on the coupled atmosphere/ocean systems in the tropical Pacific. *Meteor. Atmos. Phys.*, **44**, 29–41.

———, 1991: "The Monsoon Year"-A new concept of the climate year in the tropics. *Bull. Amer. Meteor. Soc.*, **72**, 1331–1338.

——— and Y. Seki, 1992: Role of the Asian monsoon on the interannual variability of the global climate system. *J. Meteor. Soc. Japan*, **70**, 177–189.