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Interdecadal shift in the relationship between the East Asian summer monsoon and the tropical Indian Ocean

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Abstract In this work, the authors investigate changes in the interannual relationship between the East Asian summer monsoon (EASM) and the tropical Indian Ocean (IO) in the late 1970s. By contrasting the correlations of the EASM index (EASMI) with the summer IO sea surface temperature anomaly (SSTA) between 1953–1975 and 1978–2000, a pronounced different correlation pattern is found in the tropical IO. The SSTA pattern similar to the positive Indian Ocean Dipole (IOD) shows a strongly positive correlation with the EASMI in 1953–1975. But in 1978–2000, significant negative correlation appears in the northern IO and the IOD-like correlation pattern disappears. It is indicated that the summer strong IOD events in 1953–1975 can cause a weaker-than-normal western North Pacific (WNP) subtropical high, which tends to favor a strong EASM. In 1978–2000, the connection between the summer IOD and the WNP circulation is disrupted by the climate shift. Instead, the northern IO shows a close connection with the WNP circulation in 1978–2000. The warming over the northern IO is associated with the significant enhanced 500 hPa geopotential height and an anomalous anticyclone over the WNP. The change in the IO–EASM relationship is attributed to the interdecadal change of the background state of the ocean–atmosphere system and the interaction between the ENSO and IO. In recent decades, the tropical IO and tropical Pacific have a warmer mean SST, which has likely strengthened (weakened) the influence of the northern IO (IOD) on the EASM. In addition, due to the increase in the ENSO variability along with the higher mean equatorial eastern Pacific SST in 1978–2000, the influence of ENSO on the East Asian summer circulation experiences a significant strengthening after the late 1970s. Because the warming over the northern IO is associated with the significant warming in the equatorial eastern Pacific, the strengthened ENSO–EASM relationship has likely also contributed to the strengthened relationship between the northern IO and the EASM in 1978–2000.

Keywords East Asian summer monsoon · Indian Ocean · Interdecadal shift · ENSO

1 Introduction

The Asian summer monsoon is composed of three subsystems: the Indian summer monsoon (ISM), the western North Pacific summer monsoon (WNPSM), and the East Asian summer monsoon (EASM) (Lau and Yang 1997; Ding and Chan 2005). The EASM is a sub-tropical monsoon encompassing eastern China, Japan, Korea, and the surrounding areas (20°N–45°N, 110°E–140°E) (Lau and Li 1984; Wang and Lin 2002). Because of its impacts on nearly one-third of the world's population and on the global climate system, the study of the EASM has received increased attention.

The EASM shows a great interannual variability. Numerous investigators have linked this variability to changes in the Eurasia or Tibetan Plateau snow cover (Liu and Yanai 2002) and the Pacific and Indian Ocean (IO) sea surface temperature (SST) (e.g., Huang and Wu 1989;

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Chen et al. 1992; Zhang et al. 1996; Lau and Weng 2001; Wu et al. 2000). Recent studies suggest a positive correlation between Tibetan winter snow and subsequent summer precipitation over the middle and lower reaches of the Yangtze River (Chen et al. 2000; Wu and Qian 2003). Zhang et al. (2004) further substantiate the existence of a close relationship between the interdecadal increase of snow depth over the Tibetan during the preceding spring and a wetter summer rainfall over the Yangtze River valley. It is proposed that the excessive snow results in decreases in heat sources over the Tibetan Plateau, through the increased albedo and spring snow melting, thus reducing the land–sea contrast. The land–sea temperature contrast is thought to drive the monsoon system. The decrease of the normal warming of the land surface would give rise to a weakened Asian summer monsoon.

The effect of ENSO events on the EASM and related seasonal rainfalls has been extensively studied. It has been found that above-normal rainfall in the Yangtze River valley is preceded by an El Niño event in the previous winter (Shen and Lau 1995; Chang et al. 2000). The devastating Yangtze River flood in the summer of 1998 that followed the 1997 El Niño is such an example (Lau and Weng 2001). Recently, Wang et al. (2000) have found that the circulation system that bridges the El Niño events and the East Asian climate is an anomalous low-level anticyclone located in the western North Pacific (WNP). The WNP anticyclone develops rapidly in late fall of an El Niño year and persists until the following spring or early summer, strengthening the western Pacific subtropical ridge in early summer, which then causes the abundant precipitation in the lower reaches of Yangtze River valley.

Previous studies have mainly focused on the influences of the ENSO events on the EASM interannual variability. During the recent two decades, however, the IO SST has been proposed as an important factor influencing the EASM. Saji et al. (1999) first introduced the Indian Ocean Dipole (IOD) to denote a basin-wide ocean–atmosphere coupled mode in the tropical IO. The positive IOD event is characterized by the positive SST anomalies (SSTA) in the western tropical IO and the negative SSTA in the southeastern tropical IO. Since then, many research works have documented the influences of IOD on the EASM (Li and Mu 2001; Yan and Zhang 2004; Yuan et al. 2008). In 1994, East Asian countries suffered from a record-breaking hot and dry summer climate. Guan and Yamagata (2003) showed that the abnormal 1994 East Asian summer conditions are related to the positive IOD event in 1994, which continued for more than 8 months from around March through October. Li and Mu (2001) revealed how the IOD events affect the East Asian summer climate. Different phases of the IOD mode might change the intensity of the South Asian High and the WNP subtropical high, thus changing the intensity of the EASM. Additionally, it is also presented by Guan and Yamagata (2003) that the IOD could generate Rossby wave patterns that influence the circulation changes over East Asia.

An interdecadal change was observed in the late 1970s in the tropical and North Pacific SSTs (e.g., Nitta and Yamada 1989; Graham 1994; Trenberth and Hurrell 1994; Wang 1995). The WNP subtropical high has enlarged, intensified, and shifted southwestward after the late 1970s (He and Gong 2002). The interdecadal changes of ocean–atmosphere system could strongly affect and modulate the interannual relationship between the tropical ocean SSTs and the Asian summer monsoon. Kumar et al. (1999) found that the inverse relationship between the ENSO and the ISM has weakened in recent decades. Chang et al. (2000) showed that the interannual relationship between the EASM and the tropical Pacific SSTs changes in two periods of 1951–1977 and 1978–1996. Wu and Wang (2002) also demonstrated that the ENSO–monsoon relationship in northern China and Japan has experienced a remarkable change since the late 1970s.

As an important external forcing factor of the EASM, the tropical IO SST has its distinct features of interannual variability. According to Ding et al. (2008), the correlation between the summer SSTA in the western tropical IO (6°S–10°N, 40°E–80°E) and EASM shows a distinct shift in sign from positive to negative after the late-1970s. However, the mechanisms that cause the change in the relationship between the tropical IO SST and EASM are still unknown. The present study will examine the interdecadal change in the relationship between the tropical IO SST and EASM during 1953–2000 and explore the possible causes responsible for the change in the tropical IO–EASM relationship. This paper is arranged as follows. Section 2 describes data and methods used in this study. In Sect. 3, we compare correlation patterns of the summer SSTA in the tropical IO with EASM index (EASMI) between the two periods of 1953–1975 and 1978–2000 and address relevant changes in EASM-related circulation over East Asia. In Sect. 4, we discuss the impacts of different SSTA pattern in the tropical IO on East Asian summer circulation anomalies. The possible causes for the change in the tropical IO–EASM relationship are investigated in Sect. 5. Discussion and concluding remarks are given in Sects. 6 and 7, respectively.

2 Data and methodology

The datasets used in this study include monthly mean NCEP/NCAR reanalysis data (1953–2000), monthly mean SST fields from version 2 of NOAA Extended Reconstructed SST data (1854–2005), the EASMI and the IOD index (IODI). The variables from the NCEP/NCAR reanalysis include winds at 850 hPa, geopotential height at 500 hPa, and surface temperature. The monsoons possess very strong seasonal variation, it is therefore a reasonable idea that strong and weak monsoons may be measured by use of the seasonal variation magnitude of wind field. The EASMI is defined as an area-averaged seasonally (JJA) dynamical normalized seasonality (DNS) at 850 hPa within the East Asian monsoon domain (10°N–40°N, 110°E–140°E) (Li and Zeng 2002). The DNS monsoon index is given by

$$\delta = \frac{||\overline{V}_1 - V_i||}{||\overline{V}||} - 2, \tag{1}$$

where $\overline{V}_1$ and V_i are the January climatology and monthly wind vectors at a grid point, respectively, $\overline{V}$ is the mean of January and July climatology wind vectors at the same point. In the right side of Eq. 1, the value 2 is subtracted because the critical value of significance of the quantity $||\overline{V}_1 - V_i|| / ||\overline{V}||$ is 2. In the Northern (Southern) Hemisphere, $\delta < 0$ represents winter (summer) monsoon, and $\delta > 0$ summer (winter) monsoon (see Li and Zeng 2002 for more details). There is an apparent negatively correlation between the EASMI and summer rainfall in the middle and lower reaches of Yangtze River valley, indicating drought years over the valley are associated with the strong EASM and flood years with the weak EASM. According to Saji et al. (1999), the IODI is defined as SSTA differences between the western (10°S–10°N, 50°E–70°E) and eastern (10°S–10°N, 90°E–110°E) IO. A positive IOD or positive phase means warm (cool) in the western (eastern) IO. The opposite SSTA pattern is a negative IOD or negative phase. To emphasize the interannual variability of all variables, an 11-year high-pass filter is applied to obtain the interannual anomalies. The annual cycle has been removed before the high-pass filter.

To document the interdecadal change in the tropical IO–EASM relationship, we take two periods: 1953–1975 and 1978–2000, each period consisting of 23 years. The selection of the two periods is based on the sliding correlation between the EASMI and SSTA in the tropical western IO (Fig. 4 of Ding et al. (2008)). The correlation patterns with respect to the EASMI are calculated separately for the two periods.

3 Changes of EASM-related IO SSTA and circulation anomalies between 1953–1975 and 1978–2000

3.1 SSTA in the tropical IO

To uncover where the tropical IO–EASM relationship experiences the most noticeable change in the late-1970s, we compare the correlation of summer (JJA) SSTA in the tropical IO with the EASMI between 1953–1975 and 1978–2000. The correlation pattern shows remarkable differences between the two periods. In 1953–1975, significant positive correlation is located in the western tropical IO and negative correlation is located in the eastern tropical IO (Fig. 1a). This correlation pattern is very similar to the positive IOD (Saji et al. 1999), implying that the summer IOD has a close relationship with the EASM in the previous period. In 1978–2000, significant negative correlation appears in the northern IO and the IOD-like correlation pattern disappears (Fig. 1b). Apparently, the largest change between the two periods is found in the spatial mode of EASM-related tropical IO SSTA.

To validate the evolution of the relationship between the EASM and IOD, we show the sliding correlations between the EASMI and summer IODI in Fig. 2a. Consistent with Fig. 1, the EASMI and summer IODI show a significant positive correlation before the mid-1970s, followed by an obvious weakening of correlation in the late 1970s. The temporal evolution of correlation clearly indicates that the relationship between the EASM and IOD has weakened in recent decades. On the contrary, the relationship between the EASM and summer SSTA in the northern IO has strengthened in recent decades (Fig. 2b). The correlations of the EASMI with the IODI and the northern IO SSTA nearly keep steady in the two periods chosen before and after the late-1970s. Therefore, it would be meaningful to take the two periods and compare the change of the tropical IO–EASM relationship.

3.2 Circulation anomalies over East Asia

The EASM-related circulation anomalies over East Asia show remarkable differences between the two periods. Figure 3 shows regression patterns of summer 500 geopotential height, 850 hPa winds and surface temperature anomalies with respect to the EASMI for the periods 1953–1975 and 1978–2000, respectively. In 1953–1975, the regression pattern of 500 hPa height exhibits a negative–positive–negative anomalies from low latitude to high latitude over East Asia (Fig. 3a). This pattern looks similar to the East Asia-Pacific (EAP) teleconnection pattern (Nitta 1987; Huang and Sun 1992). The significant negative anomalies over the WNP are related to the WNP subtropical high. At 850 hPa, an anomalous cyclone is found over the WNP and an anomalous anticyclone is observed in the Northeast Asia, causing northerly wind anomalies to occur in South China and southerly wind anomalies to occur in North China (Fig. 3a). Anomalous southerly winds in North China are expected to bring more moisture to North China and favor more precipitation. The surface temperature shows significant positive anomlies in the central-western China, while significant negative anomalies are

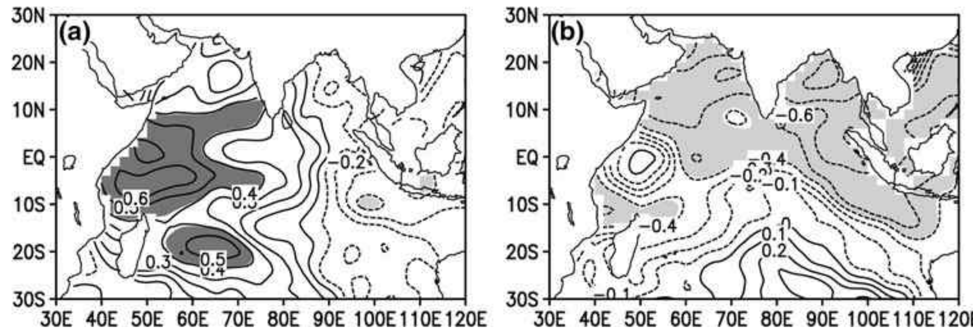

Fig. 1 Correlation of summer SSTA in the tropical IO with the EASMI in (**a**) 1953–1975 and (**b**) 1978–2000. The *values* in the *shaded areas* are significant at the 0.05 level. Contour interval is 0.1

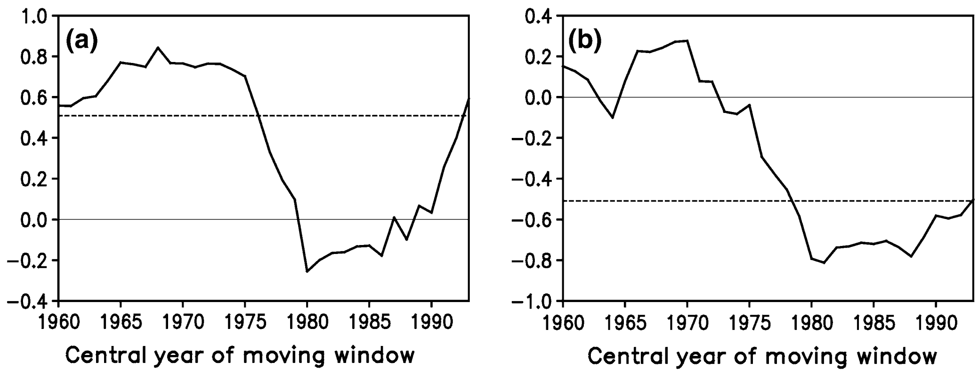

Fig. 2 15-year sliding correlations of (**a**) IODI and (**b**) area-averaged SSTA over the northern IO (5°N–25°N, 50°E–100°E) with the EASMI for summer during 1953–2000. The *horizontal dashed line* shows the 0.05 significance level

found in the high latitudes (Fig. 3a). This pattern of surface temperature tends to intensify the land–sea temperature contrast and would lead to a strong EASM.

In contrast, in 1978–2000, the EAP-like regression pattern of 500 hPa height is stronger and more significant from low latitude to high latitude over East Asia (Fig. 3b). The regions with significant anomalies show an obvious expansion and the values of positive and negative anomalies centers become greater. Especially over the WNP subtropics, the regions with significant negative anomalies extend westwardly to South Asia and extend eastwardly to the whole tropical Pacific. Moreover, the center of the negative anomalies located in Southeast Coast of China moves more northerly. The striking differences between the two periods suggest the strengthening relationship between the WNP subtropical high and the EASM after the late 1970s, which is consistent with Chang et al. (2000). At 850 hPa, anomalous cyclone over the WNP is stronger in 1978–2000 than in 1953–1975 (Fig. 3b). Northerly wind anomalies are intensified over the South China and southerly wind anomalies are weakened over the North China in 1978–2000. The surface temperature anomalies also show distinct features between the two periods. In 1978–2000, significant negative anomalies appear in the northern IO and the WNP, with a larger region and a greater value of negative anomalies in the low latitude than in 1953–1975. Another change can be noticed in the mid-latitude. The significant positive anomalies located in the central-western China in 1953–1975 moves to Northeast Asia in 1978–2000 (Fig. 3b).

The contrast of the relationship between EASMI and the East Asian summer circulation anomalies shows the strengthened linkage of the anomalous WNP circulation with the EASM in recent decades. The SSTA in the tropical IO can induce large circulation anomalies over the WNP (Wu et al. 2000; Yuan et al. 2008). Thus, one way by which the tropical IO SSTA influences the EASM is through the anomalous WNP circulation. The change in the relationship between the EASMI and the WNP circulation indicates that the impact of the tropical IO on the EASM through the anomalous WNP circulation is different before and after the late-1970s.

4 Impacts of different SSTA pattern in the tropical IO on East Asian summer circulation anomalies

Why does the positive IOD SSTA pattern positively correlate with the EASMI in 1953–1975 but the northern IO SSTA negatively correlate with the EASMI in 1978–2000? In two different periods, the different responses of East Asian summer circulation to distinct SSTA patterns in the tropical IO may play an important role in the difference in correlation. In this section, we discuss the impacts of different SSTA patterns in the tropical IO on the East Asian summer circulation anomalies.

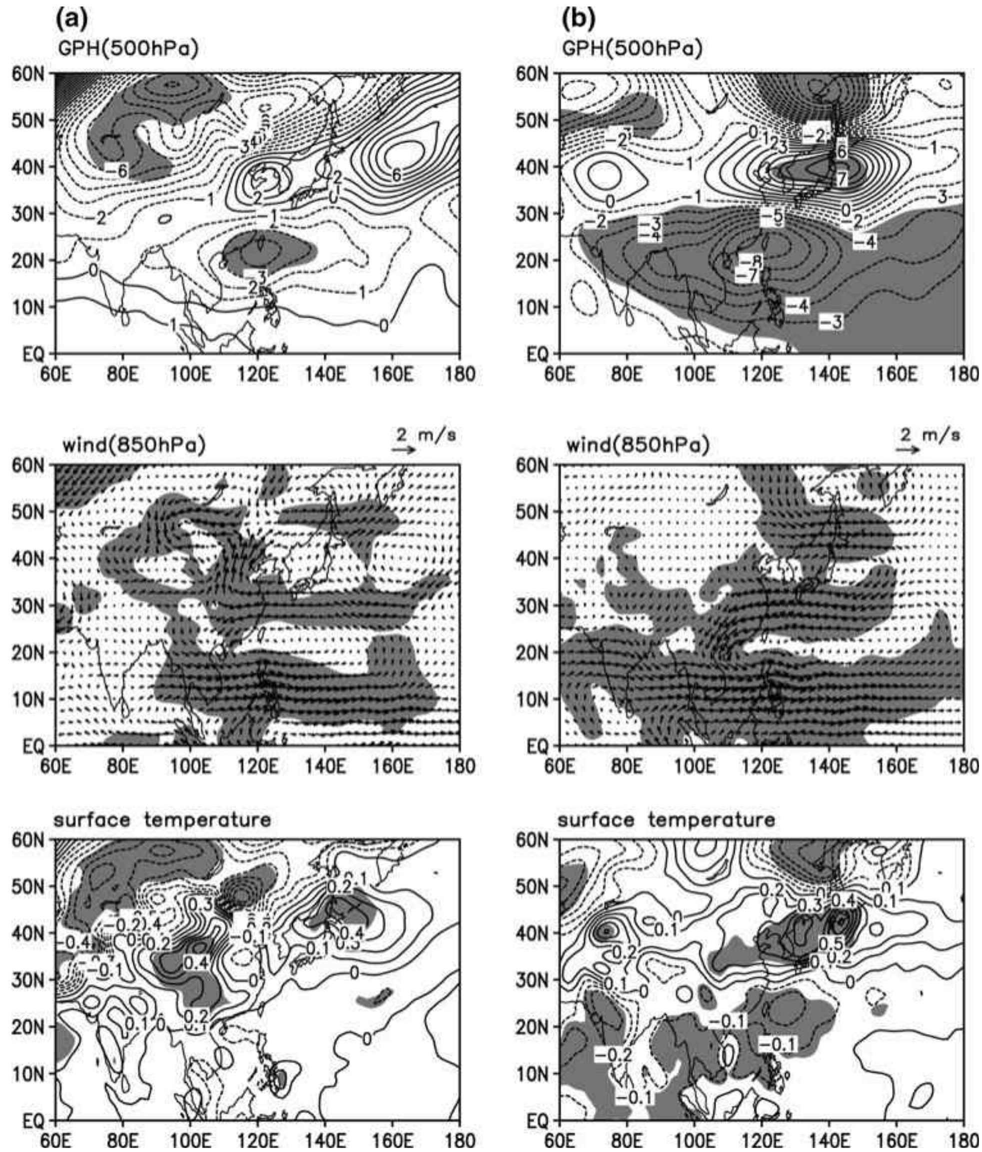

Fig. 3 Regression pattern of summertime circulation anomalies with respect to the EASMI for (**a**) 1953–1975 and (**b**) 1978–2000. From *top* to *bottom* are 500 hPa height, 850 hPa winds, and surface temperature, respectively. The contour interval is 1 gpm for 500 hPa height and 0.1°C for surface temperature. The *values* in the *shaded areas* are significant at the 0.05 level

According to the summer IODI in 1953–2000, we choose six summer high IODI years (1961, 1967, 1972, 1982, 1983, 1994) with the summer IODI greater than one standard deviation of the index, and five summer low IODI years (1964, 1969, 1971, 1984, 1996) with the summer IODI less than one negative standard deviation of the index. There are three summer high IODI years (1961, 1967, 1972) and three summer low IODI years (1964, 1969, 1971) in 1953–1975. In addition, three summer high IODI years (1982, 1983, 1994) and two summer low IODI years (1984, 1996) are included in 1978–2000. Figure 4 shows the composite differences of summer 500 heights, 850 hPa winds, and surface temperature between summer high and low IODI years in the two periods before and after the late-1970s. For the strong summer IOD years of 1953–1975, the composite summer 500 hPa heights show negative–positive–negative anomalies from the WNP to high latitude over East Asia, indicating the weaker-than-normal WNP subtropical high during the strong summer IOD event (Fig. 4a). At 850 hPa, an anomalous cyclone is found over the WNP, causing anomalous northerly winds to occur over the southeastern China. Anomalous southerly winds are observed over the North China (Fig. 4a). Surface temperatures are considerably warmer in the central-western China and the Northeast Asia during the strong summer IOD years of 1953–1975 (Fig. 4a). These composite differences of summer 500 hPa heights, 850 hPa winds, and surface temperature in 1953–1975 are quite similar to the EASM-related summer circulation patterns shown in Fig. 3a, suggesting the significantly positive relationship between the summer IOD and EASM in 1953–1975. The existences of warm land surface anomalies and positive geopotential anomalies over the Northeast Asia during positive IOD events are also found by Saji and Yamagata (2003).

The composite differences of summer circulation fields between summer high and low IODI years in 1978–2000 show remarkable differences compared with those in 1953–1975. For the strong summer IOD years of 1978–2000, summer 500 hPa heights show positive-negative-positive anomalies from the WNP to high latitude over East Asia (Fig. 4b), which are very different from those in 1953–1975. At 850 hPa, no obvious wind anomalies are found in the southeastern and northern China (Fig. 4b). The surface temperature in 1978–2000 are characterized by the warming at mid-high latitudes over Eurasia (Fig. 4b). Compared with the EASM-related summer circulation patterns in 1978–2000, the summer situations over East Asia corresponding to strong summer IOD do not tend to favor a considerably strong or weak EASM. The differences in the connection between the summer IOD and the East Asian summer circulation anomalies in the two periods may account for the weakened relationship between the summer IOD and EASM in recent decades.

Similar to the selection of high and low summer IOD years, if the area-averaged SSTA over the region (5°N–25°N, 50°E–100°E) is defined as the northern IO SST index (NIOI), we choose six summer high NIOI years (1958, 1970, 1983, 1987, 1988, 1998) with the summer NIOI greater than one standard deviation of the index, and eight summer low NIOI years (1955, 1956, 1971, 1978, 1984, 1985, 1989, 1994) with the NIOI index less than one negative standard deviation of the index. There are two summer high NIOI years (1958, 1970) and three summer low NIOI years (1955, 1956, 1971) in 1953–1975. Besides, four summer high NIOI years (1983, 1987, 1988, 1998) and five summer low NIOI years (1978, 1984, 1985, 1989,

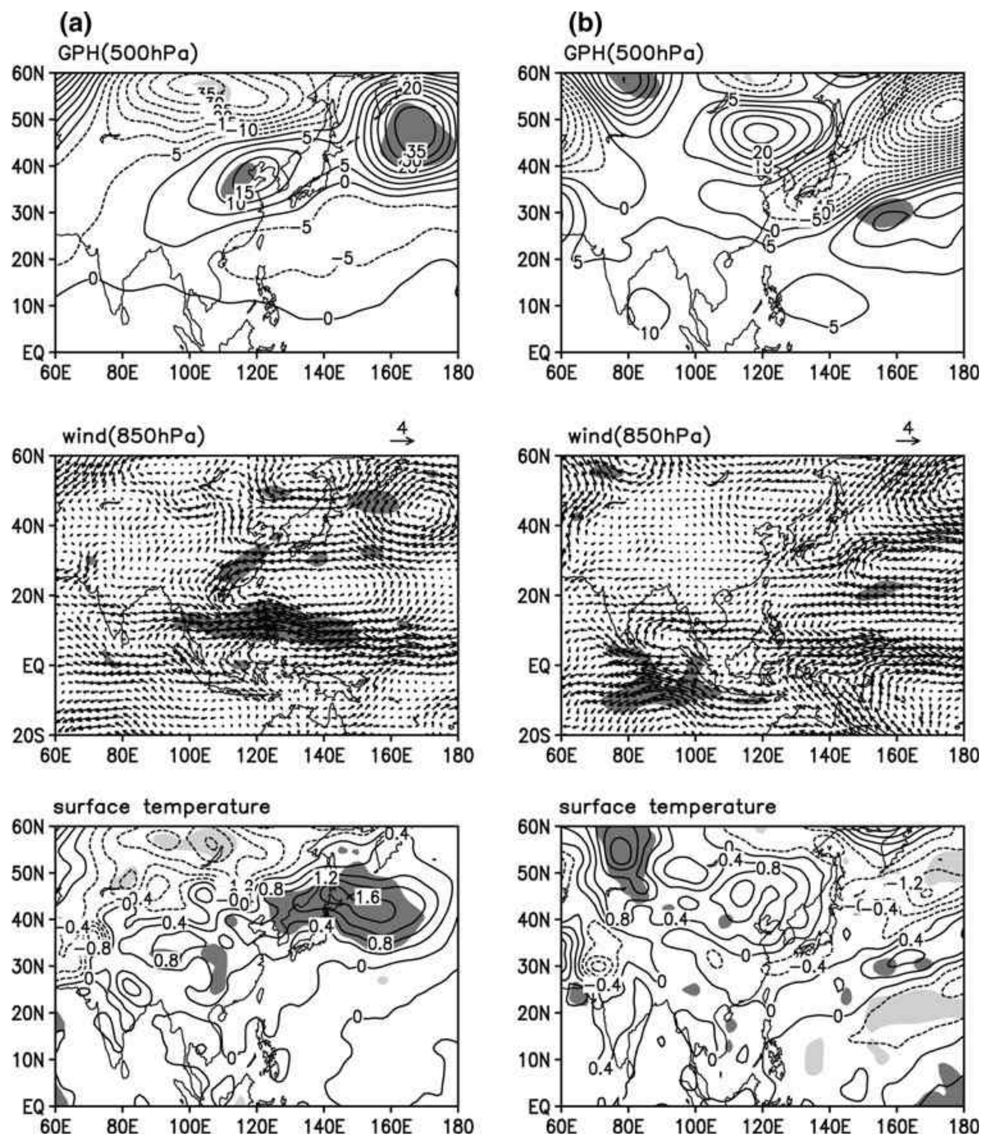

Fig. 4 Composite differences of summertime circulation anomalies between the summer high and low IODI years in (**a**) 1953–1975 and (**b**) 1978–2000. From *top* to *bottom* are 500 hPa height, 850 hPa winds, and surface temperature, respectively. The contour interval is 5 gpm for 500 hPa height and 0.4°C for surface temperature. The *values* in the *shaded areas* are significant at the 0.05 level of *t* test

1994) are included in 1978–2000. Figure 5 shows the composite differences of summer 500 heights, 850 hPa winds, and surface temperature between the summer high and low NIOI years respectively in 1953–1975 and in 1978–2000. Corresponding to the summer high NIOI years in 1978–2000, 500 hPa geopotential heights in summer show positive-negative-positive anomalies from the WNP to high latitude over East Asia. Especially, 500 hPa heights over the WNP and the tropical Pacific and tropical IO are significantly higher during the summer high NIOI events (Fig. 5b). At 850 hPa, the anomalous easterly winds occur over the regions from the western tropical Pacific to the Indian. Meanwhile an anomalous anticyclone is found over the WNP, causing anomalous southerly winds to occur over the southeastern China. Anomalous northerly winds are observed over the North China (Fig. 5b). Consistent with the summer high SST over the northern IO, the surface temperature also shows obvious warming over the northern IO during the high summer NIOI events in 1978–2000, reducing the summer land–sea contrast needed to sustain a strong monsoon (Fig. 5b). The anomalous easterly winds in 850 hPa occurring over the northern IO are coherent with the reduction of land–sea surface temperature gradient. These composites differences of summer 500 hPa height, 850 hPa winds, and surface temperature corresponding to the summer high NIOI events in 1978–2000 are exactly opposite to the EASM-related summer circulation patterns shown in Fig. 3b, suggesting the significantly negative relationship between the summer SSTA over the northern IO and EASM in 1978–2000.

The composite differences of summer 500 heights, 850 hPa winds, and surface temperature between the summer high and low NIOI years show distinct features between the two periods. In 1953–1975, although 500 geopotential heights in summer are significantly higher in the tropical Pacific and tropical IO when the northern IO SSTA become warmer, 500 geopotential height over the WNP and the southeastern China is not significantly enhanced. Besides, only a very small region with significantly decreased geopotential height is found over south of Korea (Fig. 5a), while relatively large region with significantly decreased geopotential height is located in Japan in 1978–2000. At 850 hPa, only anomalous northerly winds occur in the eastern part of China for the summer high NIOI years in 1953–1975 (Fig. 5a). The composite summer surface temperature shows less warming over the northern IO in 1953–1975 than in 1978–2000. The significant cooling occurring over the northern Japan in 1978–2000 moves to South of Japan in 1953–1975 (Fig. 5a). These differences in the composite differences of summer circulation anomalies between the two periods cause a significant correlation in 1978–2000 and a weak correlation in 1953–1975 between the northern IO SSTA and EASM.

In summer 1994, it can be noted that the positive IOD occurs in the tropical IO, accompanied by anomalous cooling over the northern IO (Fig. 6). Guan and Yamagata (2003) found an anomalous cyclonic circulation over the WNP and the southern China and an anomalous anticyclonic circulation around Japan, Korea, and the northeastern part of China in summer 1994. They attributed the abnormal East Asian summer conditions to the strong positive IOD event in 1994. However, from the above analysis, it is very possible that the anomalous cyclone over the WNP and the anomalous anticyclone around Japan, Korea, and the northeastern China are mainly related to the anomalous cooling over the northern IO in summer 1994. The strong positive IOD event in 1994 has likely also, to some degree, contributed to the abnormal East Asian summer circulation, but does not play a decisive role. In other years (1971, 1983, 1984) besides 1994, the IOD SSTA pattern and positive or negative SSTA over the northern IO in summer occur at the same time. For the year (1971) in 1953–1975, the IOD possibly plays an important role in abnormal East Asian summer circulation. On the contrary, for the years (1983, 1984) in 1978–2000, the SSTA over the northern IO possibly contribute greatly to abnormal East Asian summer circulation. However, for the particular years, the situation may be different. The relative importance of different influences of the IOD and the northern IO SSTA on the EASM in different periods needs further exploration in the future.

5 Possible causes for the change in the tropical IO–EASM relationship

The identified changes in the correlations between the EASMI and the summer SSTA over the tropical IO raise a question: What caused the change in the response of the East Asian summer circulation to the tropical IO SSTA? One possible reason is the interdecadal change of the background state of the ocean-atmosphere system. In the recent decades, the tropical IO and tropical Pacific have a warmer mean SST. The composite difference of summer surface temperature climatologies of 1978–2000 and 1953–1975 shows that summer surface temperature is considerably warmer over the tropical IO and tropical western Pacific and considerably cooler over the Asian continent in 1978–2000 (Fig. 7). The weakened land–sea thermal gradient conductive for a weak summer monsoon is favored. The interannual increase of summer SSTA over the northern IO is superposed on a warmer mean SST in 1978–2000, which would contribute to a stronger effect of the land–sea contrast in weakening the Asian summer monsoon. In addition, the increases of mean SST over the tropical Pacific and IO could lead to the interdecadal

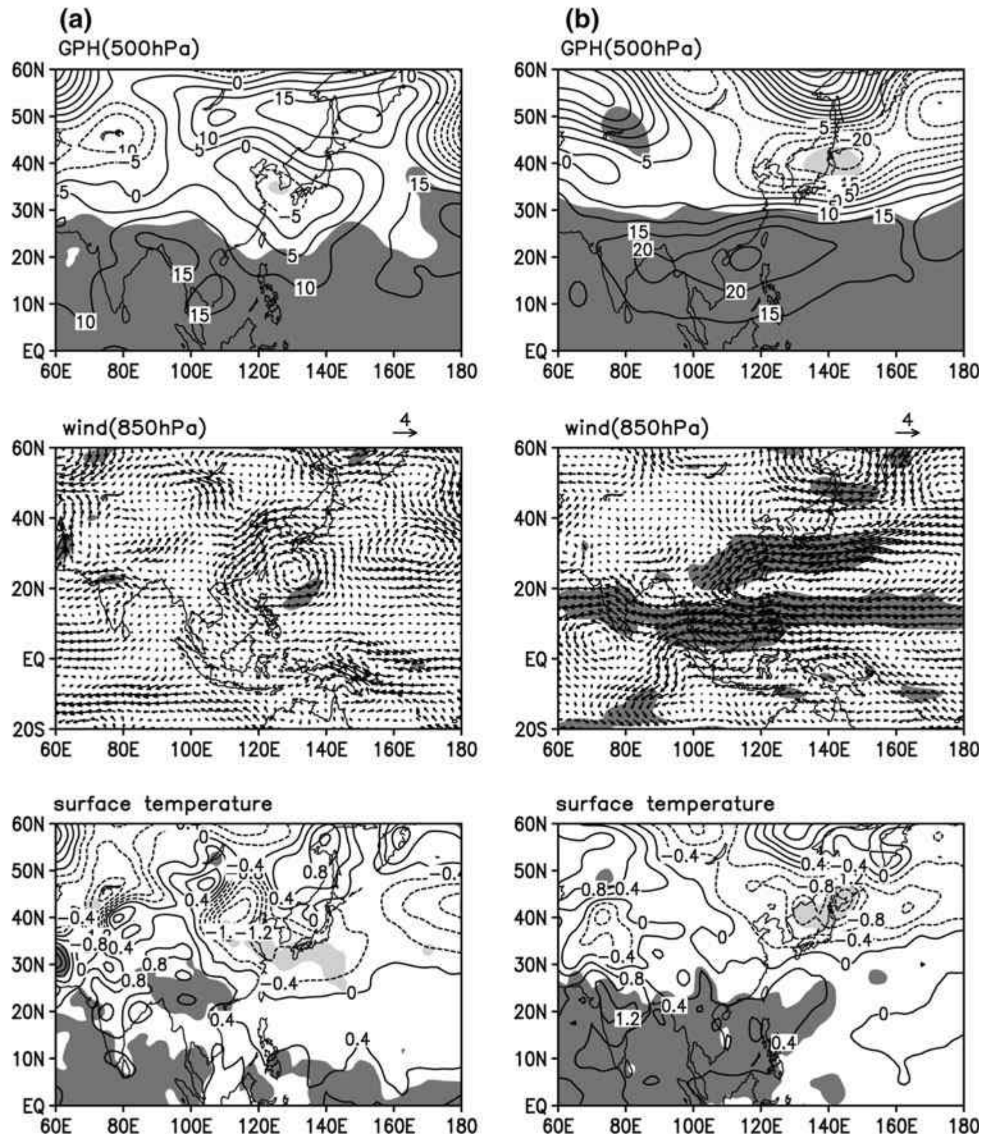

Fig. 5 Same as Fig. 4, but for the composite differences between the summer high and low NIOI years in (**a**) 1953–1975 and (**b**) 1978–2000

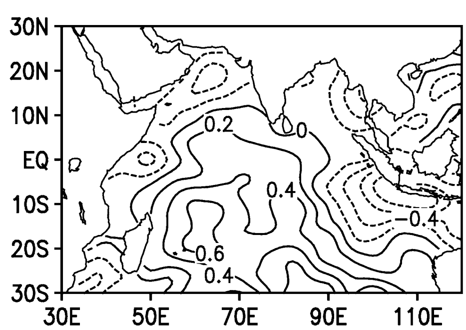

Fig. 6 Summer SSTA (in °C) in the tropical IO during 1994

intensification of the WNP subtropical high (He and Gong 2002), which would strengthen the influences of the WNP subtropical high on the EASM. It can be noted from Fig. 5 that the responses of the WNP subtropical high to the warming over the northern IO are stronger in 1978–2000 than 1953–1975. The strengthened relationship between the northern IO and the WNP subtropical high would therefore intensify the linkage between the northern IO SSTA and the East Asian summer circulation in the recent decades.

Another possible reason for the strengthened influences of the northern IO SSTA on EASM in 1978–2000 is the interaction between the ENSO and IO. A number of studies have investigated the interaction between the ENSO and IO (Venzke et al. 2000; Xie et al. 2002; Huang and Kinter 2002; Lau and Nath 2003; Krishnamurthy and Kirtman 2003; Kug and Kang 2006). It has been observed that during El Niño event, when positive SSTA form in the equatorial Pacific, positive SSTA also tend to develop in the tropical IO (Klein et al. 1999). The Walker circulation is thought to provide a mechanism linking ENSO and IO variability. Figure 8a shows that for the strong summer

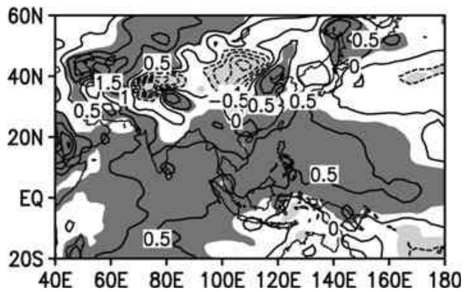

Fig. 7 Composite difference of the summer surface temperature (in °C) between 1978–2000 and 1953–1975. The *values* in the shaded areas are significant at the 0.05 level of *t* test

IOD years in 1953–1975, the negative SSTA of the previous winter are found in the equatorial eastern Pacific and the positive SSTA are found in the tropical western Pacific, implying that a weak La Niña pattern occurs. On the contrary, for the strong summer IOD years in 1978–2000, an obvious El Niño pattern occurs in the tropical Pacific of the previous winter, with the positive SSTA in the equatorial eastern Pacific and the positive SSTA in the tropical western Pacific (Fig. 8b). According to Wang et al. (2000), the El Niño (La Niña) events could induce an anomalous low-level anticyclone (cyclone) over the WNP, which would persists until the ensuing summer, strengthening (weakening) the western Pacific subtropical ridge in early summer. The strong summer IOD years in 1953–1975 are shown to be related to the weakened WNP subtropical high, which is same as the effect of the previous winter La Niña events on the WNP subtropical high, thus intensifying the relationship between the summer IOD and EASM. However, taking into account the weak La Niña pattern in the equatorial eastern Pacific, the effect of the previous winter SSTA in the tropical Pacific accompanied by the summer IOD events in 1953–1975 on the WNP subtropical high is insignificant. The summer IOD events in 1953–1975 possibly exert independent influence on the EASM. In 1978–2000, if the strong summer IOD events tend to weaken WNP subtropical high as before, the summer IOD and the associated El Niño events of the previous winter would exert opposite influences on the WNP subtropical high, thus disrupting the influence of the summer IOD on EASM. This process appears to be responsible for the weakened relationship between the summer IOD and EASM in 1978–2000.

Besides, although the warming over the northern IO in 1953–1975 and 1978–2000 is both associated with the significant warming in the equatorial eastern Pacific (Fig. 8c, d), the higher mean equatorial eastern Pacific SST in 1978–2000 could force a stronger anomalous anticyclone near the east Asian monsoon region than in 1953–1975. This may contribute to a stronger effect of the ENSO on the EASM. The negative correlation between the EASMI and the previous winter Niño-3 SSTA shows an obvious strengthening in 1978–2000 (Fig. 9). The results suggest that the strengthened relationship between the northern IO and the EASM may be partly due to the strengthened relationship between the ENSO and the EASM in 1978–2000.

6 Discussion

It has been shown that the influences of the northern IO and ENSO on EASM are strengthened after the late 1970s. The interannual variability of EASM could therefore be changed. Figure 10 shows that the interannual variability of the EASMI becomes greater and the period of the EASMI tends to shorten after the late-1970s. By the power spectrum analysis, it is found that the main interannual oscillation period of the EASMI has experienced a significant change in the different periods. In 1953–1975, the interannual variation of the EASMI is dominated by a period of about 7 years (Fig. 11a). But In 1978–2000, the EASMI shows an obvious quasi-biennial oscillation (QBO) with a period of about 2–3 years (Fig. 11b). Similar results have been found by Yang (2005), who indicates that the dominant period of summer rainfall over the Yangtze-Huaihe river valley changes from about 7 years to about 2 years after the late 1970s. Shen and Lau (1995), using 1956–1985 data, found a strong biennial signal in the correlations between EASM (as represented by rainfall over China) and the tropical SST. Figure 12a shows the lag correlations between the EASMI and the northern IO SSTA in 1953–1975 and 1978–2000, respectively. In 1978–2000, their lag correlations show an evident QBO relationship between the EASM and the northern IO. A weak EASM is closely related to the warm northern IO in the previous autumn and the ensuing summer and the cold northern IO in the following early summer. But in 1953–1975, the correlations between the EASM and the northern IO are almost positive and the QBO relationship between the EASM and the northern IO is insignificant. A similar situation happens to the relationship between the equatorial eastern Pacific SSTA and EASMI. It is shown that the QBO relationship between the equatorial eastern Pacific and EASMI is also more robust in 1978–2000 than 1953–1975 (Fig. 12b). These results suggest that the evident quasi-biennial signal of EASM in 1978–2000 possibly results from the interactions of the EASM with the northern IO and tropical Pacific, which provides another evidence for the strengthened relationship between the northern IO and EASM in recent decades.

In addition, defining the intensity of the EASM has been highly controversial due to the complexity of the EASM variability. Up to now, many kinds of the EASM indices

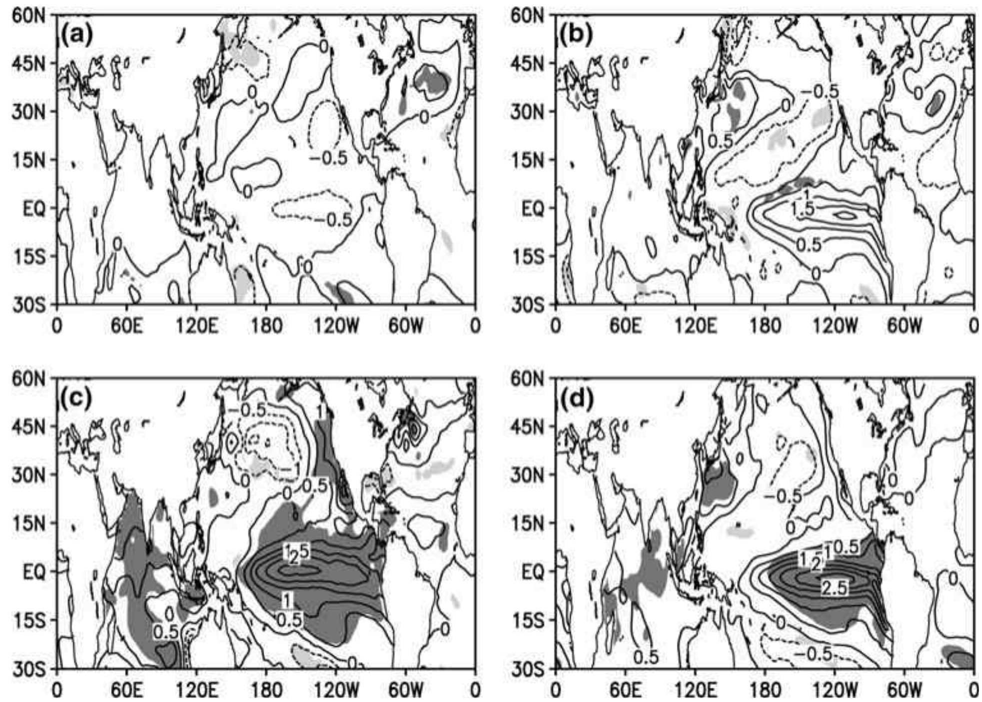

Fig. 8 **a** and **b** are the composite differences of previous winter SSTA between the summer high and low IODI years in 1953–1975 and 1978–2000, respectively. **c** and **d** are the composite differences of previous winter SSTA in the summer high and low NIOI years in 1953–1975 and 1978–2000, respectively. The contour interval is 0.5°C. The *values* in the *shaded areas* are significant at the 0.05 level of *t* test

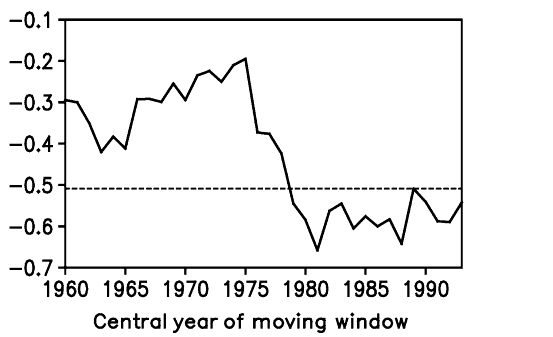

Fig. 9 Same as Fig. 2, but for 15-year sliding correlations between the EASMI and the previous winter Niño-3 (5°S–5°N, 150°W–90°W) SSTA during 1953–2000

have been proposed to measure the EASM intensity (Wang et al. 2008). These existing indices show different advantages and limitations. The EASMI used in this paper quantifies the EASM variability by gauging the strength of the low-level East Asian monsoon winds using the 850 hPa southwesterly winds. According to Wang et al. (2008), this index captures the leading modes of EASM variability well. In order to validate the change of the relationship between the EASM and the tropical IO SSTA, the summer rainfall over the Yangtze River region (28°N–32°N, 110°E–120°E) is used to compute the sliding correlations with the summer IODI and the northern IO SSTA, respectively. It is indicated that the summer rainfall over the Yangtze River region and the summer IOD exhibits a good relationship in 1953–1975 (Fig. 13a). In 1978–2000, the northern IO SSTA in place of the IOD shows a good relationship with the summer rainfall over the Yangtze River region (Fig. 13b). The results are consistent with those shown in Fig. 2, confirming that the impact of the tropical IO on the EASM is very different before and after the late 1970s. However, because the seasonal mean precipitation anomalies over the East Asia often exhibit large meridional variations, the relationship between the tropical IO and the summer rainfall over different regions possibly

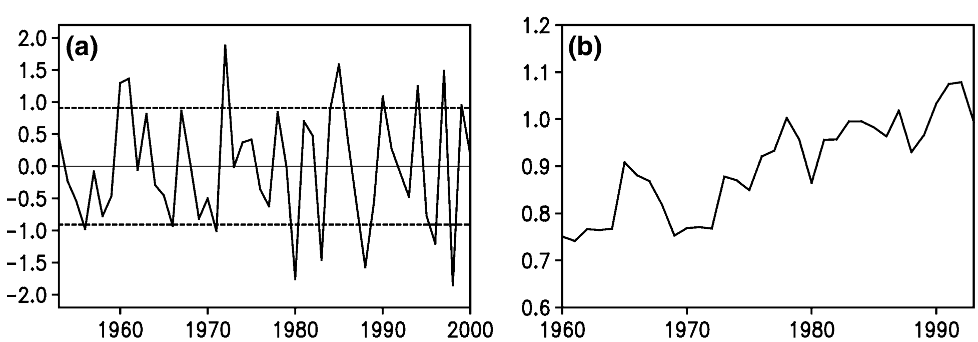

Fig. 10 Interannual variation of EASMI during 1953–2000 (**a**) and standard deviation of EASMI calculated within a 15-year window that moves year by year from 1953 to 2000 (**b**). In **a** the *dashed line* indicates the one positive and negative standard deviation of the index, respectively

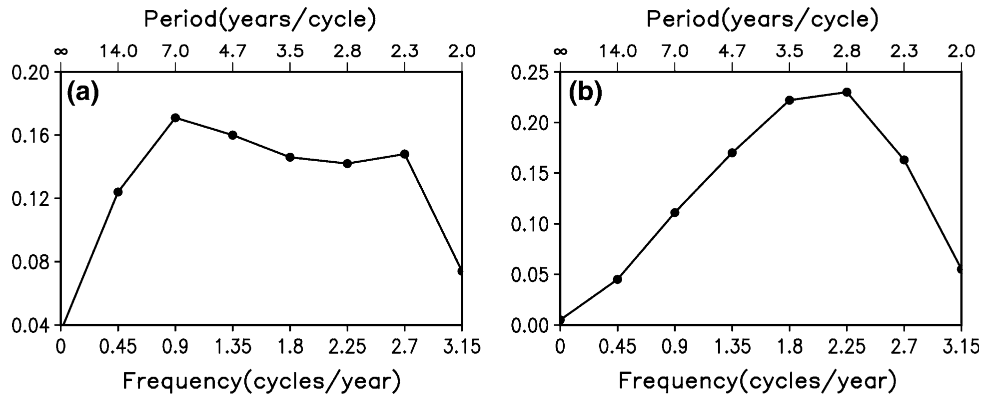

Fig. 11 Power spectrum of the EASMI in (**a**) 1953–1975 and (**b**) 1978–2000

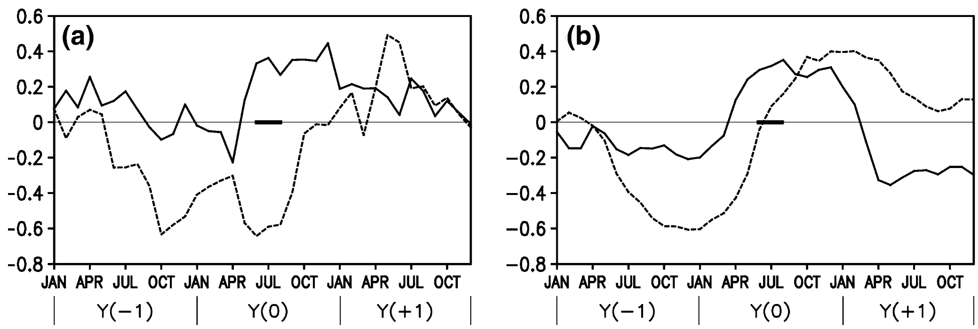

Fig. 12 Lagged correlations between the EASMI and the monthly SSTA in **a** the northern IO and **b** the Niño-3 region. The correlations computed using 1953–1975 and 1978–2000 data are indicated by the *solid line* and *dashed line*, respectively. $Y(-1)$ and $Y(+1)$ refer to the year before and after the reference year $Y(0)$. The June–August summer monsoon season is marked by a *horizontal bar*

experiences a different change. Further study is necessary to examine the changes of relationship between the tropical IO and the summer rainfall over different regions.

7 Summary and concluding remarks

This study compares the correlation of the EASMI with the summer IO SSTA between 1953–1975 and 1978–2000. A pronounced different correlation pattern is found in the tropical IO. The IOD-like SSTA pattern shows a strongly positive correlation with the EASMI in 1953–1975. But in 1978–2000, significant negative correlation appears in the northern IO and the IOD-like correlation pattern disappears.

One way by which the tropical IO SSTA influences the EASM is through the anomalous WNP circulation. It is indicated that the summer strong IOD events in 1953–1975 can cause a weaker-than-normal WNP subtropical high, which tends to favor a strong EASM. In 1978–2000, the connection between the summer IOD and the WNP circulation is disrupted. When the summer strong IOD events occur, no obvious changes in the WNP circulation are observed. Instead, the northern IO shows a close connection with the WNP circulation in 1978–2000. The warming over the northern IO is associated with the significant

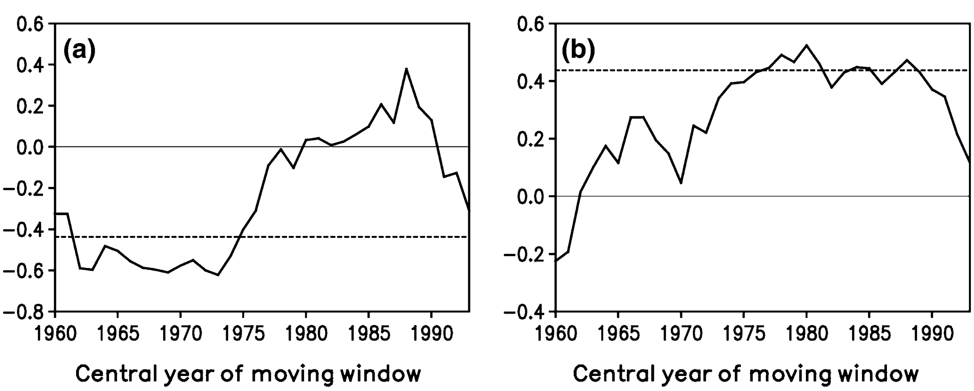

Fig. 13 Same as Fig. 2, but for 15-year sliding correlations of **a** summer IODI and **b** summer area-averaged SSTA over the northern IO (5°N–25°N, 50°E–100°E) with the area-averaged summer rainfall over the Yangtze River region (28°N–32°N, 110°E–120°E) during 1953–2000. The *horizontal dashed line* shows the 0.1 significance level

enhanced 500 hPa geopotential height and an anomalous anticyclone over the WNP.

One cause for the weakened (strengthened) relationship between the EASM and the summer IOD (the northern IO) after the late 1970s may be the interdecadal change of the background state of the ocean-atmosphere system. In the recent decades, the tropical IO and tropical Pacific have a warmer mean SST. The warming over the northern IO superposed on a warmer mean SST in 1978–2000, would contribute to a stronger effect of the land–sea contrast in weakening the EASM. The interdecadal intensification of the WNP subtropical high possibly results from the warming over the northern IO and tropical Pacific. The response of the WNP subtropical high to the warming over the northern IO is stronger in 1978–2000 than 1953–1975, thus intensifying the linkage between the northern IO and the EASM.

Another cause for the weakened (strengthened) relationship between the EASM and the summer IOD (the northern IO) after the late 1970s may be the interaction between the ENSO and IO. It is indicated that the warming over the northern IO is associated with the significant warming in the equatorial eastern Pacific. Due to the increase in the ENSO variability along with the higher mean equatorial eastern Pacific SST in 1978–2000, the influence of ENSO on the East Asian summer circulation experienced a significant strengthening after the late 1970s. To some degree, the strengthened ENSO–EASM relationship would contribute to the strengthened relationship between the northern IO and the EASM in 1978–2000. In 1953–1975, the influence of ENSO on the relationship between the IO and the EASM is insignificant and the summer IOD events possibly exert independent influence on the EASM.

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