Interdecadal Change of the Relationship Between the Tropical Indian Ocean Dipole Mode and the Summer Climate Anomaly in China*

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ABSTRACT

The interdecadal change of the relationship between the tropical Indian Ocean dipole (IOD) mode and the summer climate anomaly in China is investigated by using monthly precipitation and temperature records at 210 stations in China and the NCEP/NCAR reanalysis data for 1957–2005. The results indicate that along with the interdecadal shift in the large-scale general circulation around the late 1970s, the relationship between the IOD mode and the summer climate anomaly in some regions of China has significantly changed. Before the late 1970s, a developing IOD event is associated with an enhanced East Asian summer monsoon, which tends to decrease summer precipitation and increase summer temperature in South China; while after the late 1970s, it is associated with a weakened East Asian summer monsoon, which tends to increase (decrease) precipitation and decrease (increase) temperature in the south (north) of the Yangtze River. During the next summer, following a positive IOD event, precipitation is increased in most of China before the late 1970s, while it is decreased (increased) south (north) of the Yangtze River after the late 1970s. There is no significant correlation between the IOD and surface air temperature anomaly in most of China in the next summer before the late 1970s; however, the IOD tends to increase the next summer temperature south of the Yellow River after the late 1970s.

Key words: tropical Indian Ocean dipole (IOD), summer climate anomaly in China, interannual variability, interdecadal change

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1. Introduction

It is widely recognized that sea surface temperature (SST) in the tropical Indian Ocean features considerable variabilities. Observational analyses have identified two dominant modes in the SST variabilities in the tropical Indian Ocean. One is the uniform basin-wide mode closely associated with the El Niño/Southern Oscillation (ENSO) (Lanzante, 1996; Klein et al., 1999; Zhou et al., 2004; Tan et al., 2003), and the other is the so-called Indian Ocean dipole (IOD) mode (Saji et al., 1999; Webster et al., 1999). Like the ENSO cycle, the IOD mode is phase-locked to seasonal cycle, maturing in boreal autumn and decaying in winter and next spring (Saji and Yamagata, 2003). The relationship between the IOD mode and ENSO is quite complicated. Some scientists believed that the IOD mode is influenced by the ENSO (Allan

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et al., 2001; Xie et al., 2002; Krishnamurthy and Kirtman, 2003; Tan et al., 2004; Zhong et al., 2005), while others pointed out that it is independent of the ENSO (Yamagata et al., 2003; Qian et al., 2003). The IOD-related SST anomalies in the tropical Indian Ocean can exert significant impacts on the East Asian summer monsoon and associated summer climate anomaly in China. Numerical simulations have shown that the positive SST anomalies in the eastern tropical Pacific and Indian Ocean tend to weaken the East Asian and Indian summer monsoons (Zou and Liu, 2002). However, considering the possible independence of the IOD mode, we speculate that the impact of the IOD mode on the East Asian summer climate may be different from that of the ENSO. Therefore, it is of interest to probe into the role of the IOD mode in the East Asian climate variability.

Some observational analyses have revealed a significant relationship between the IOD mode and the summer precipitation anomaly in China. Xiao et al. (2002) documented that the East Asian trough appears to be weaker and the western Pacific subtropical high extends more southward, leading to more precipitation in South China but less in North China, when the IOD is in its positive phase. Li and Mu (2001) pointed out that, during a positive IOD phase, the anticyclone over the Tibet and the western Pacific subtropical high are weaker, while the South China Sea and Indian summer monsoons are enhanced, which can significantly influence the summer precipitation in South China. Tang and Sun (2005) showed that during a positive IOD phase, the convective activity over the Philippines is weakened and the East Asian summer monsoon is stronger with more precipitation in South China; while during a negative IOD phase, the atmospheric circulation is characterized by an opposite anomaly pattern with more precipitation between the Yellow and Yangtze River valleys. Numerical experiments have confirmed the observed impact of the IOD mode on the climate variability of China (Xiao et al., 2000; Yan and Zhang, 2004).

The global climate system experienced a remarkable interdecadal shift in the late 1970s. For example, the ENSO features different characteristics during the pre- and post–1970s (Wang, 1995; An and Wang, 2000), and the relationship between the ENSO and the summer climate variability in China has also changed (Torrence and Webster, 1999; Wang, 2002; Xu and Wang, 2000; Zhu and Yang, 2003). Under such a background interdecadal shift, the East Asian summer monsoon also exhibits significant interdecadal variations with a clear three-dimensional structure over East Asia (Yu and Zhou, 2007; Yu et al., 2004). An interdecadal cooling in the upper troposphere over East Asia is found, which tends to strengthen the westerlies south of the East Asian jet through an anomalous upper-level cyclone and to weaken the East Asian summer monsoon through an anomalous lower-level anticyclone (Yu et al., 2004; Li et al., 2005; Xin et al., 2006). The tropical Indian Ocean SST variability also experienced an interdecadal change in the late 1970s. The first Empirical Orthogonal Function (EOF) of the tropical Indian Ocean SST anomaly during autumn displays a uniform basin-wide mode during the pre-1970s, while a dipole mode during the post-1970s (Annamalai et al., 2005). It is therefore interesting to examine the relationship between the IOD mode and the summer climate anomaly in China under different decadal backgrounds.

2. Data and method

Monthly precipitation and surface air temperature records at 210 stations in China and the NCEP/NCAR monthly reanalysis data (Kalnay et al., 1996) are used in this study. All the data are taken for the common period 1957–2005 and band-filtered to retain interannual variability (from 12 mon to 8 yr). Following Saji et al. (1999), a so-called IOD index is defined as the area-averaged SST anomaly in the tropical western Indian Ocean (10°S–10°N, 50°–70°E) and in which the SST anomaly in the tropical southeastern Indian Ocean (10°S–0°, 90°–110°E) is subtracted. The IOD index is calculated for September–November (autumn), and the precipitation and temperature anomalies are computed for June–August (summer). The sliding correlation in a moving window with a 21-yr width is used to reveal the relationship between the IOD mode and the summer climate interannual variability in China. The composite analysis is used to examine typical summer atmospheric circulation anomalies over East Asia for positive and negative IOD events under different interdecadal backgrounds, respectively.

3. Relationship between IOD and summer climate anomaly in China

3.1 Summer climate anomaly and autumn IOD index

Figure 1 shows the spatial distributions of the sliding correlations between the summer precipitation anomalies in China and the autumn IOD index on the interannual timescale. During 1957–1977 (Fig. 1a), a striking feature is that the summer precipitation

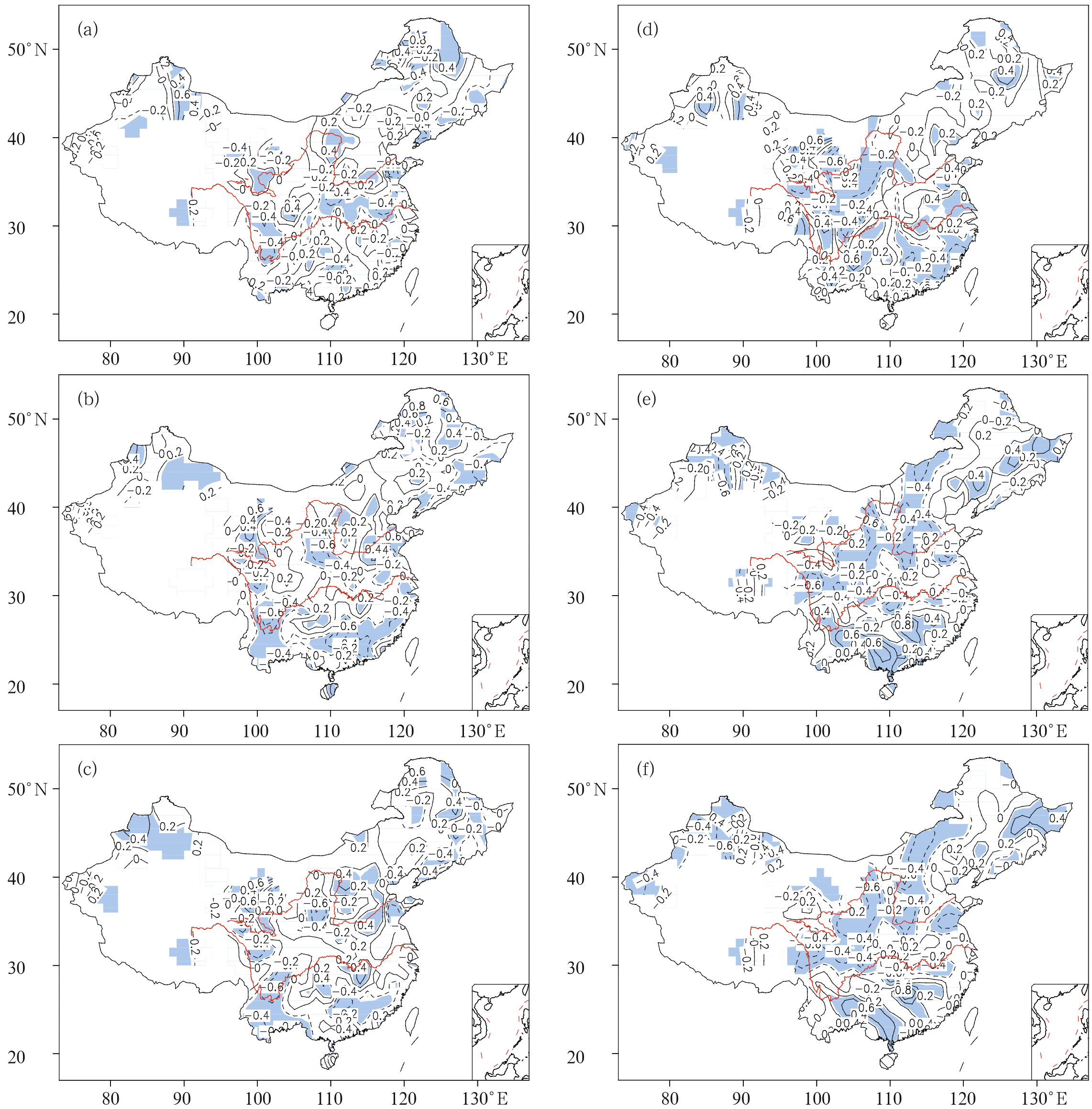

Fig. 1. The sliding correlation coefficients between the summer precipitation anomalies in China and the autumn IOD index for (a) 1957–1977, (b) 1962–1982, (c) 1967–1987, (d) 1972–1992, (e) 1977–1997, and (f) 1982–2002. Shadings indicate areas with the confidence level larger than 95%.

anomalies in most of China are negatively correlated with the IOD index, while the precipitation anomalies in northern Xinjiang Autonomous Region and northwestern Heilongjiang Province are positively correlated with the IOD index. During 1982–2002 (Fig. 1f), significant negative correlations are located in the north of the Yangtze River valley, especially in North China and the eastern part of Northwest China, while positive correlations are found in South China and eastern part of Northeast China. This is consistent with the result of Xiao et al. (2002). It can be seen from Figs. 1a–f that the summer precipitation anomalies between the Yangtze River and Huanghe valley are consistently negatively correlated with the IOD index. There is an obvious interdecadal change from the significant negative to positive correlation in South China. The spatial pattern of the interannual correlation changed significantly in the late 1970s (Fig. 1e).

In order to further investigate the inderdecadal change in the sliding correlations shown above, the regions with significantly changing correlations are selected and the sliding correlations between the summer precipitation anomalies averaged over these regions

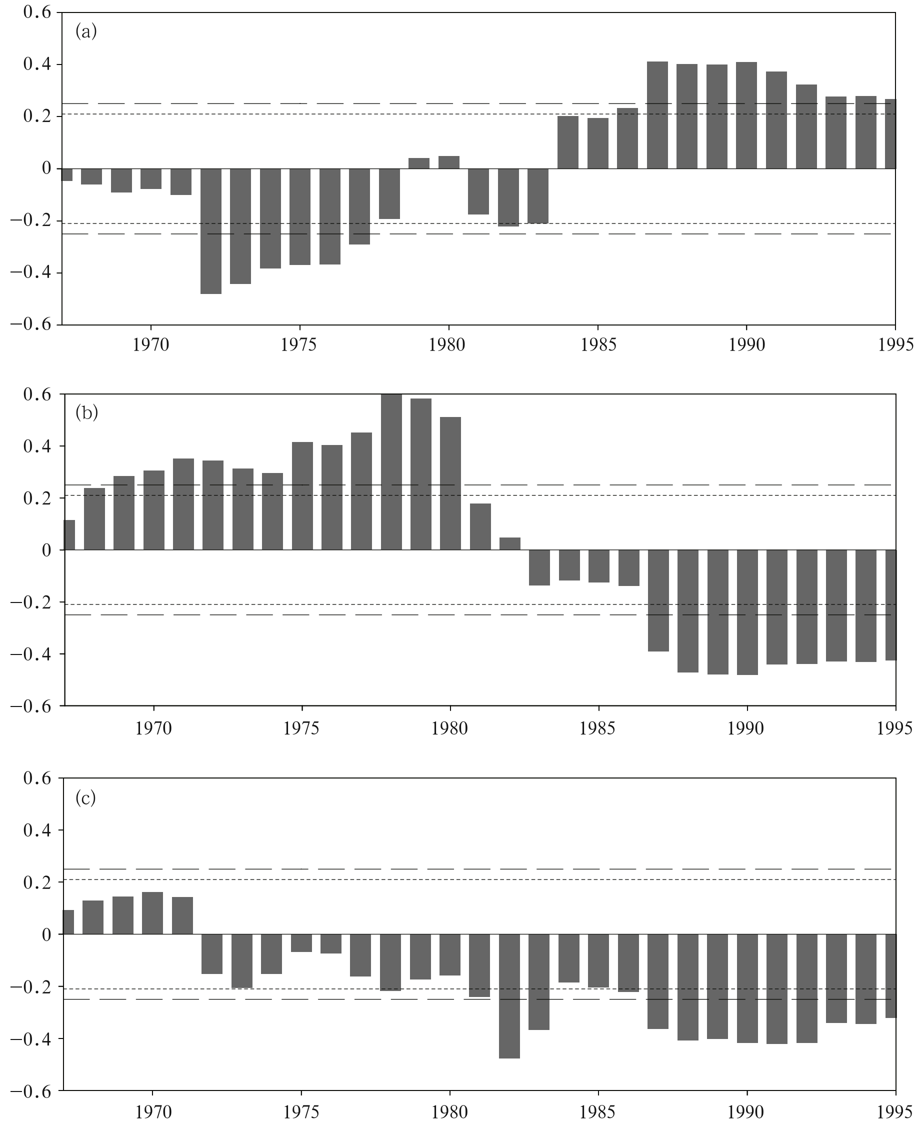

Fig. 2. The time series of the sliding correlation between the autumn IOD index and the summer precipitation anomalies averaged over (a) South China, (b) northern Xinjiang, and (c) Hetao. The dotted and dashed lines indicate confidence levels more than 90% and 95%, respectively.

and the autumn IOD index are calculated. Three regions are selected to denote South China (21 stations within 20°–27°N, 105°–120°E), northern Xinjiang (9 stations), and Hetao (10 stations within 35°–42°N, 104°–110°E), respectively. Figure 2 shows the time series of the sliding correlations for the three selected regions. It can be seen that the correlations between the IOD index and summer precipitation anomalies in South China changed significantly from negative values to positive ones around the end of 1970s (Fig. 2a), while those in northern Xinjiang changed in an opposite way (Fig. 2b). The IOD index exhibits significant negative correlations with summer precipitation anomalies in the Hetao area since the 1980s (Fig. 2c). Overall, the relationships between IOD index and summer precipitations in China changed significantly around the end of 1970s. Afterwards, the correlations tends to strengthen.

Similarly, the sliding correlations between the summer air temperature anomalies and the autumn IOD index are calculated to examine the impact of the IOD on the summer air temperature anomalies in China under different interdecadal backgrounds (Fig. 3). The IOD mode exhibits little impact on the sum-

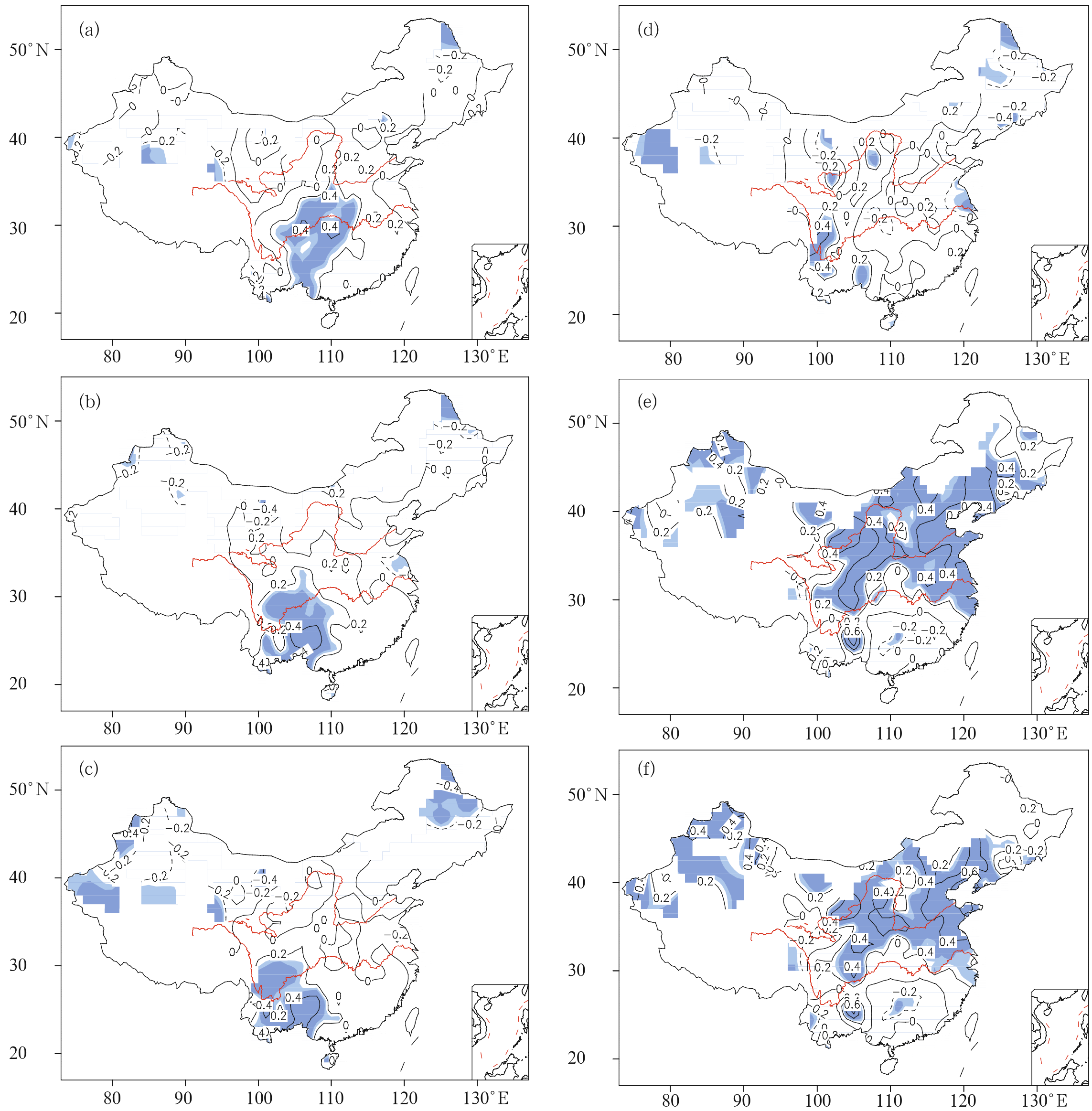

Fig. 3. As in Fig. 1, but for temperature anomalies.

mer temperature anomalies in most of China except the eastern part of Southwest China during 1957–1977 (Fig. 3a). During 1982–2002 (Fig. 3f), the IOD is positively correlated with the summer temperature anomalies north of the Yangtze River valley while negatively correlated with those south of the Yangtze River valley. The summer temperature anomalies in Sichuan Province have robust positive correlations with the IOD (Figs. 3a–f). However, there is a change from significant negative to positive correlations in the northern Xinjiang Autonomous Region, while there is a significant change from positive correlations to negative ones in South China. The relationships between the IOD and the summer temperature anomalies are significantly changed in the 1970s (Fig. 3e). Yan and Zhang (2004) also found that the summer air temperature anomalies in northwestern China are higher than normal, especially in Xinjiang, while lower in South China during a positive IOD phase.

Similar to Fig. 2, we select two representative regions: Sichuan basin (17 stations within 28°–34°N, 99°–110°E) and northern Xinjiang. It can be seen that the IOD index has persistent positive correlations with the summer temperature anomalies in Sichuan basin (Fig. 4a), except during a period of early 1980s when correlations are not significant. The correlations in northern Xinjiang changed from negative values to positive ones at the beginning of 1980s and the correlations tend to be significant since 1987 (Fig. 4b). Overall, the correlations between the IOD index and the summer temperature anomalies in both Sichuan basin and northern Xinjiang changed significantly at the end of 1970s.

3.2 Autumn IOD index and next-summer climate anomaly

The sliding correlations between the autumn IOD index and the next summer precipitation anomalies in China are shown in Fig. 5. During 1957–1977, the precipitation anomalies in most parts of China (mainly South China and northern Southwest China) are positively correlated with the IOD, while negatively correlated in Northeast China and northern Xinjiang

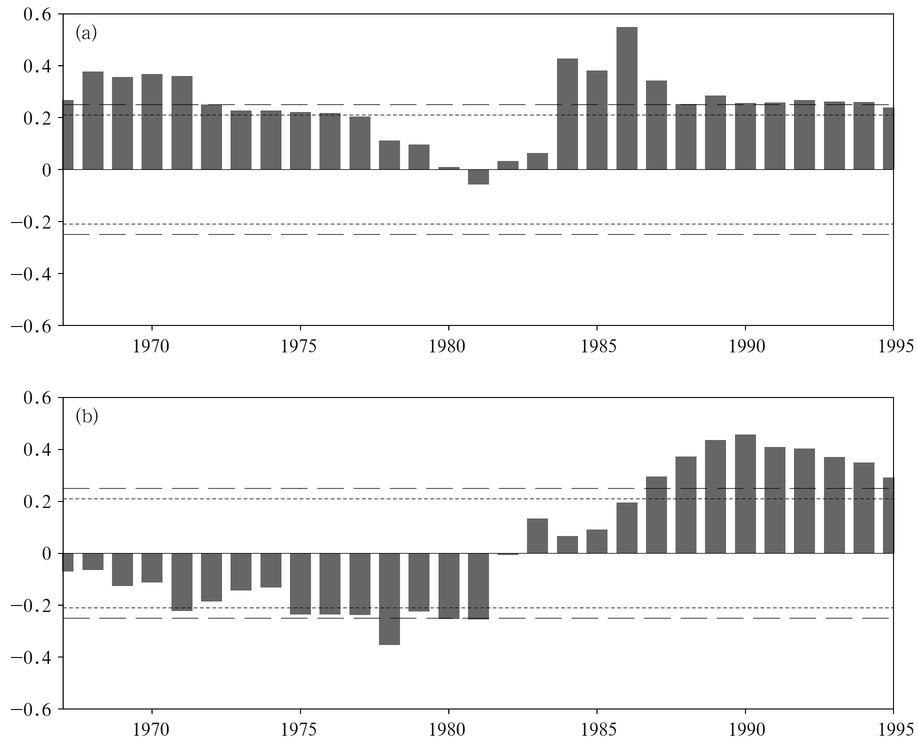

Fig. 4. As in Fig. 2, but for summer temperature anomalies over (a) Sichuan basin and (b) northern Xinjiang.

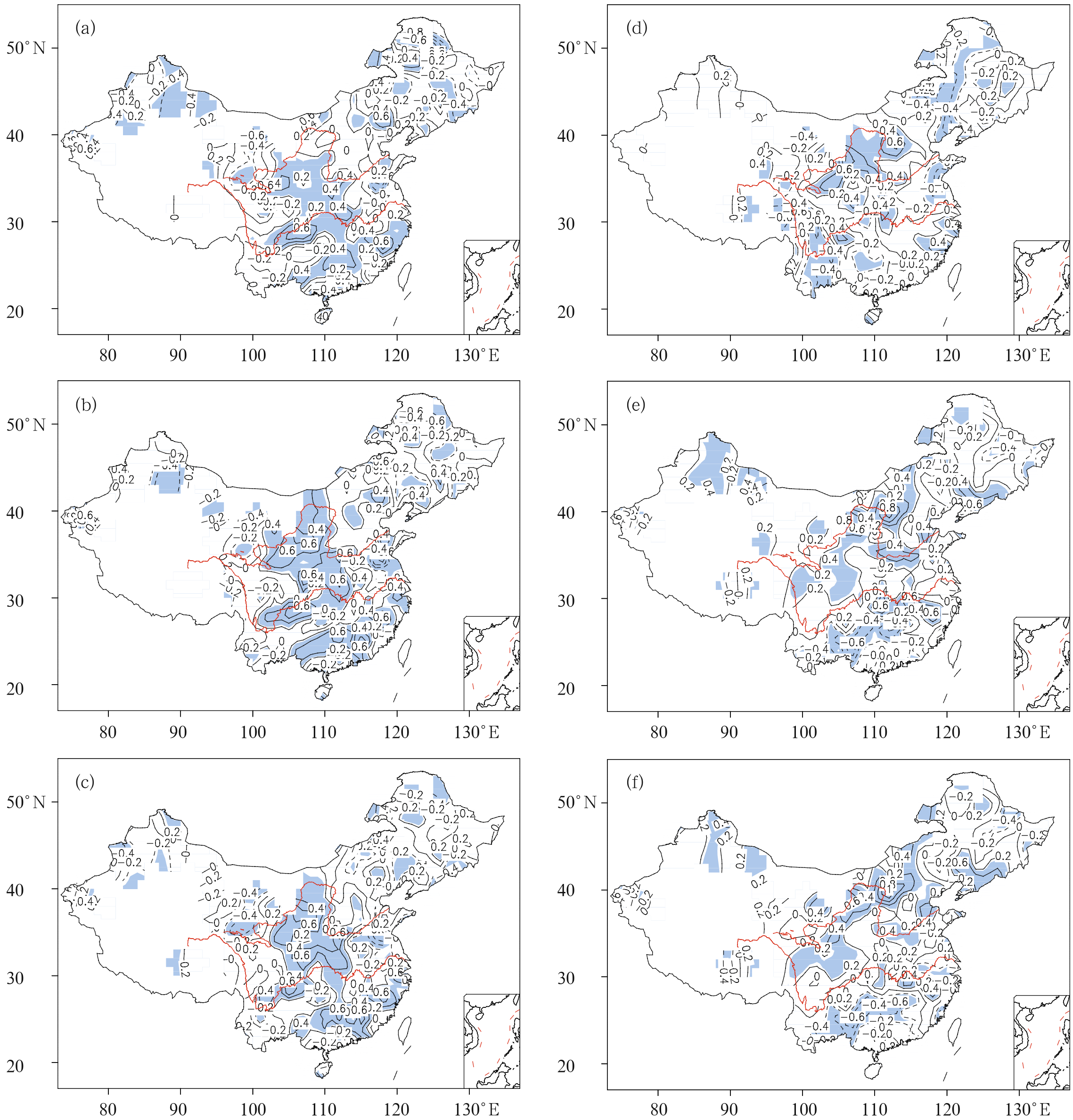

Fig. 5. The sliding correlation coefficients between the autumn IOD index and the next summer precipitation anomalies in China for (a) 1957–1977, (b) 1962–1982, (c) 1967–1987, (d) 1972–1992, (e) 1977–1997, and (f) 1982–2002. Shadings indicate areas with the confidence level larger than 95%.

(Fig. 5a). During 1982–2002, the precipitation anomalies are positively correlated with the IOD in the north of the Yangtze River valley while negatively correlated in the south (Fig. 5f). This pattern is opposite to that shown in Fig. 1f. The sliding correlations (Figs. 5a–f) show that the positive correlations are interdecadally weakened in eastern Northwest China and northeastern Southwest China. There is a significant interdecadal change from positive to negative correlation in South China while an opposite change in northern Xinjiang. Therefore, the relationship between the IOD and the next summer precipitation anomalies had a significant change from the late 1970s to the early 1980s (Figs. 5b and 5e).

During 1957–1977, the correlations between the IOD index and the next summer air temperature anomalies are negative in the Hetao area and Sichuan Province while positive in northern Xinjiang. However, there is no significant correlation in other regions of China (Fig. 6a). The summer air temperature anomalies south of the Yellow River valley are positively correlated with the IOD during 1982–2002 (Fig. 6f). During 1957–2002, there is no persistent significant correlation in most parts of China. The correlations are weakened from the late 1970s to the early 1980s (Fig. 6d). Consequently, the relationship between the IOD and the next summer air temperature anomalies in China is not robust. The IOD mainly exerts its impact on those in South China since the late 1970s.

Hence, the above analyses suggest that the IOD exerts more impacts on the next summer precipitation than on air temperature anomalies. Since the early 1980s, a positive IOD event has been related to less precipitation and higher air temperature in the next summer in South China.

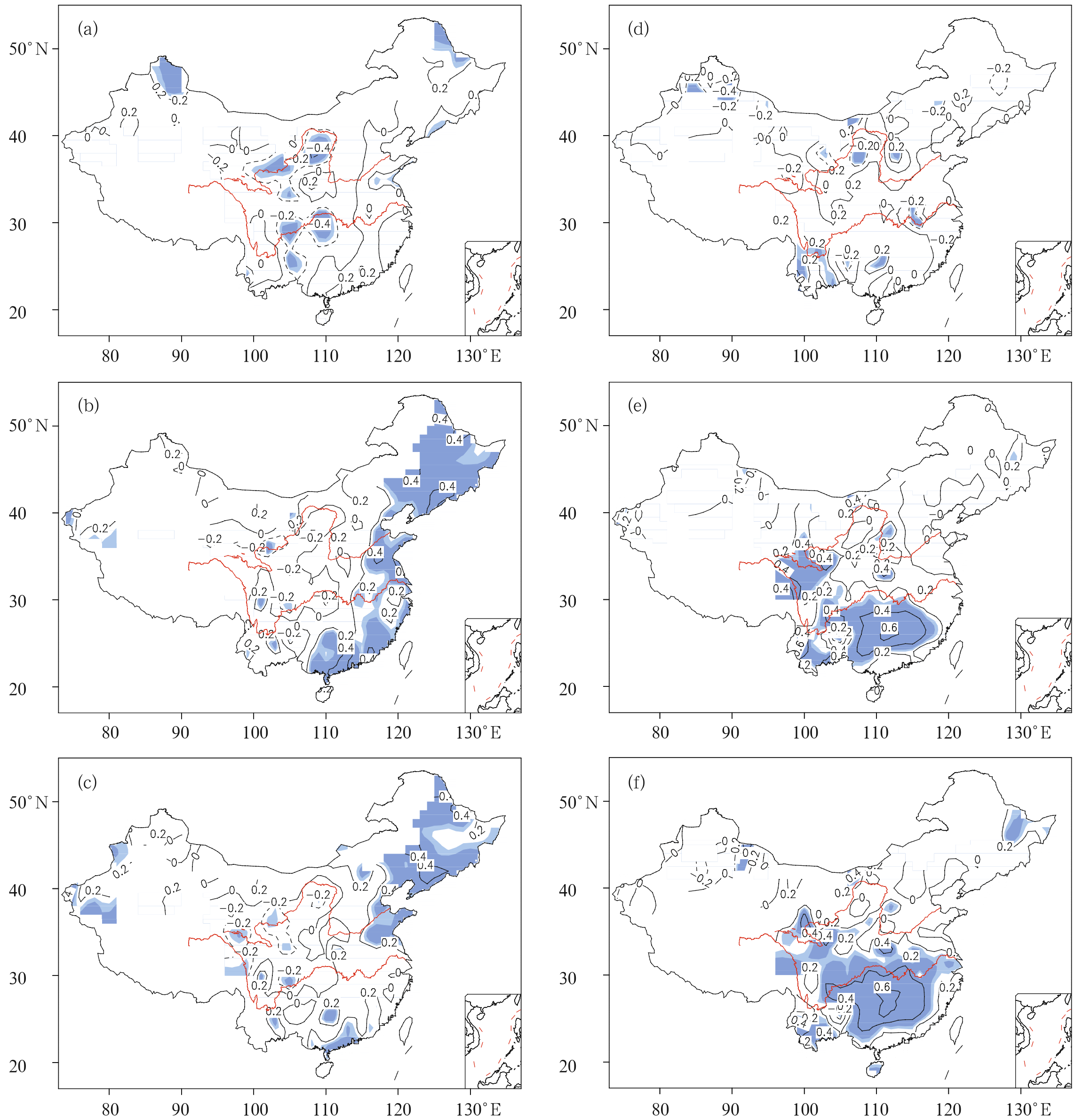

Fig. 6. As in Fig. 5, but for temperature anomalies.

4. IOD-related summer atmospheric circulation anomaly over East Asia

4.1 During the same year

In order to understand the possible physical mechanism responsible for the IOD-related atmospheric circulation anomalies for different interdecadal epoches, composites in terms of 9 positive IOD events (1961, 1963, 1967, 1972, 1977, 1982, 1994, 1997, and 2003; Saji et al., 2003; Yamagata et al., 2003) during the pre- and post-1970s are made, respectively.

The summer atmospheric circulation anomalies over East Asia for positive IOD events during the pre- and post-1970s are shown in Fig. 7. During the pre-1970s, the composite 200-hPa geopotential height is anomalously positive over the tropical Indian Ocean and negative over the Tibetan Plateau (Fig. 7a). This indicates that the South Asian high is weakened when the geopotential height over North China, Northeast China, and Inner Mongolia is strengthened. The pos-

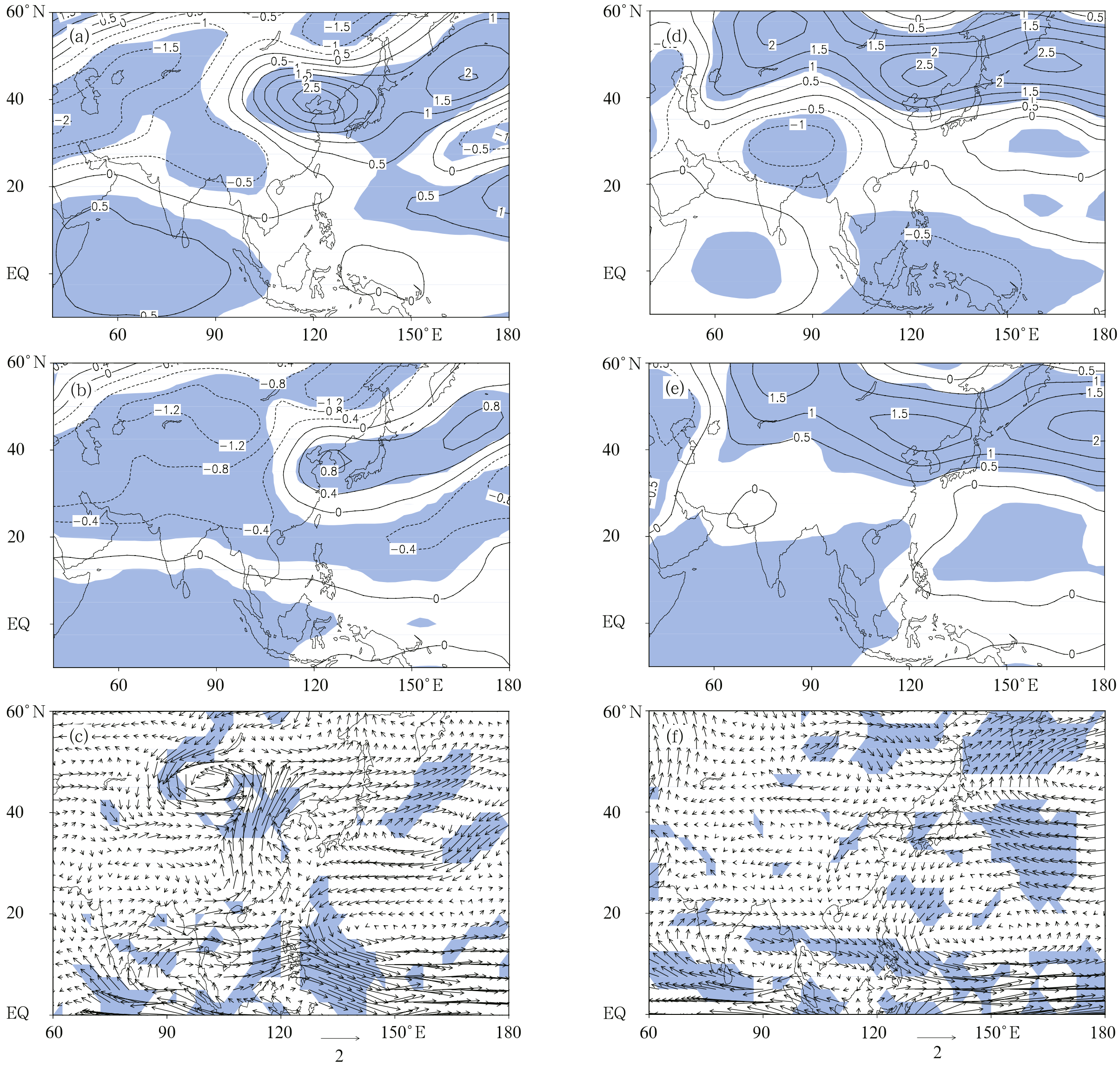

Fig. 7. Composite anomalies of summer 200- (a, d; gpm) and 500-hPa (b, e; gpm) geopotential height, and 850-hPa wind (c, f; m s^{-1}) over East Asia in the developing phase of a positive IOD event during (a–c) 1957–1977 and (d–f) 1978–2005. Shadings indicate areas with the 95% confidence level.

itive 500-hPa geopotential height anomalies (Fig. 7b) are found over the region from North China to Japan and over the tropical Indian Ocean. There are southeasterly anomalies over the equatorial Indian Ocean, westerly anomalies over the region from South Asia to Southeast Asia, and southerly anomalies over entire eastern China (Fig. 7c). An anomalous anticyclonic circulation stretches from the Bay of Bengal to Indochina Peninsula, an anomalous anticyclonic circulation occupies east of Japan, an anomalous cyclonic circulation resides over the tropical western Pacific, and an anomalous cyclonic circulation appears over Mongolia. The Indian monsoon, South China Sea monsoon, and East Asian monsoon are all strengthened.

Compared to the period 1957–1977, the summer atmospheric circulation anomalies related to the positive IOD events during 1978–2005 exhibit an obvious change over East Asia. As shown in Fig. 7d, at 200 hPa, there are positive geopotential height anomalies extending from North China to Japan and over the tropical Indian Ocean, while an anomalous cyclonic circulation exists over the Tibetan Plateau. At 500 hPa (Fig. 7e), positive geopotential height anomalies exist from the Lake of Balkhash to Sea of Okhotsk and negative anomalies exist over the tropical western Pacific. The South Asian high is much more weakened (Fig. 7d) than during the previous epoch (Fig. 7a). At 850 hPa (Fig. 7f), the wind anomalies in the tropical regions are similar to those in Fig. 7c. The tropical monsoon is enhanced. However, the distinction of Fig. 7f from Fig. 7c is that there are northerly anomalies over eastern China, which is indicative of weakening of the East Asian summer monsoon. This is why there is increase of summer precipitation in South China during the post-1970s (Figs. 1e and 1f).

The above analyses suggest that during the developing phase of an IOD event, summer atmospheric circulation anomalies over East Asia are considerably different during the pre- and post-1970s. During the epoch before 1977, a developing IOD event is associated with an enhanced East Asian summer monsoon, inducing southerly anomalies in eastern China and more precipitation in North China and high temperature in eastern Southwest China. During the epoch after 1977, a developing IOD event is associated with a weakened East Asian summer monsoon, inducing northerly anomalies in eastern China, more precipitation in South China and high temperature in North China.

4.2 During the next summer

During 1958–1978, the connections between the IOD events and the next summer atmospheric circulation anomalies are overall weak. The 200-hPa geopotential height (Fig. 8a) is anomalously high over the region from eastern Lake Baikal to western Japan, and over the tropical western Pacific. There exists an anomalous anticyclonic circulation over the region from eastern Lake Baikal to western Japan. The 500-hPa geopotential height (Fig. 8b) anomalies are positive from Northeast China to eastern Japan, and the northwestern Pacific subtropical high is strengthened. At 850 hPa (Fig. 8c), the southeasterly anomalies from the tropical western Pacific affect China. During 1977–2005, the relationship between the IOD and the atmospheric circulation anomaly in the next summer is relatively strong. At 200 hPa (Fig. 8d), the South Asian high is stronger and located more westward. An anomalous cyclonic circulation is dominant over South China, and an anomalous anticyclonic circulation extends from North China to Japan. The western Pacific subtropical high is stronger and shifts westward (Fig. 8e). At 850 hPa (Fig. 8f), the easterly anomalies are found to stretch from the tropical western Pacific to east of India. The tropical summer monsoon is weakened. The northwestern Pacific subtropical high is strengthened and located more westward, which favors less precipitation in South China.

The above analyses indicate that the IOD impacts the next summer climate anomaly in China through changing the atmospheric circulations over East Asia. During 1957–1976, a positive IOD event causes southerly anomalies over South China, Hetao area, and Sichuan Province, inducing more precipitation in those regions in the next summer. During 1977–2005, a positive IOD event leads to an enhanced South Asian high and an enhanced western Pacific subtropical high, resulting in less precipitation in

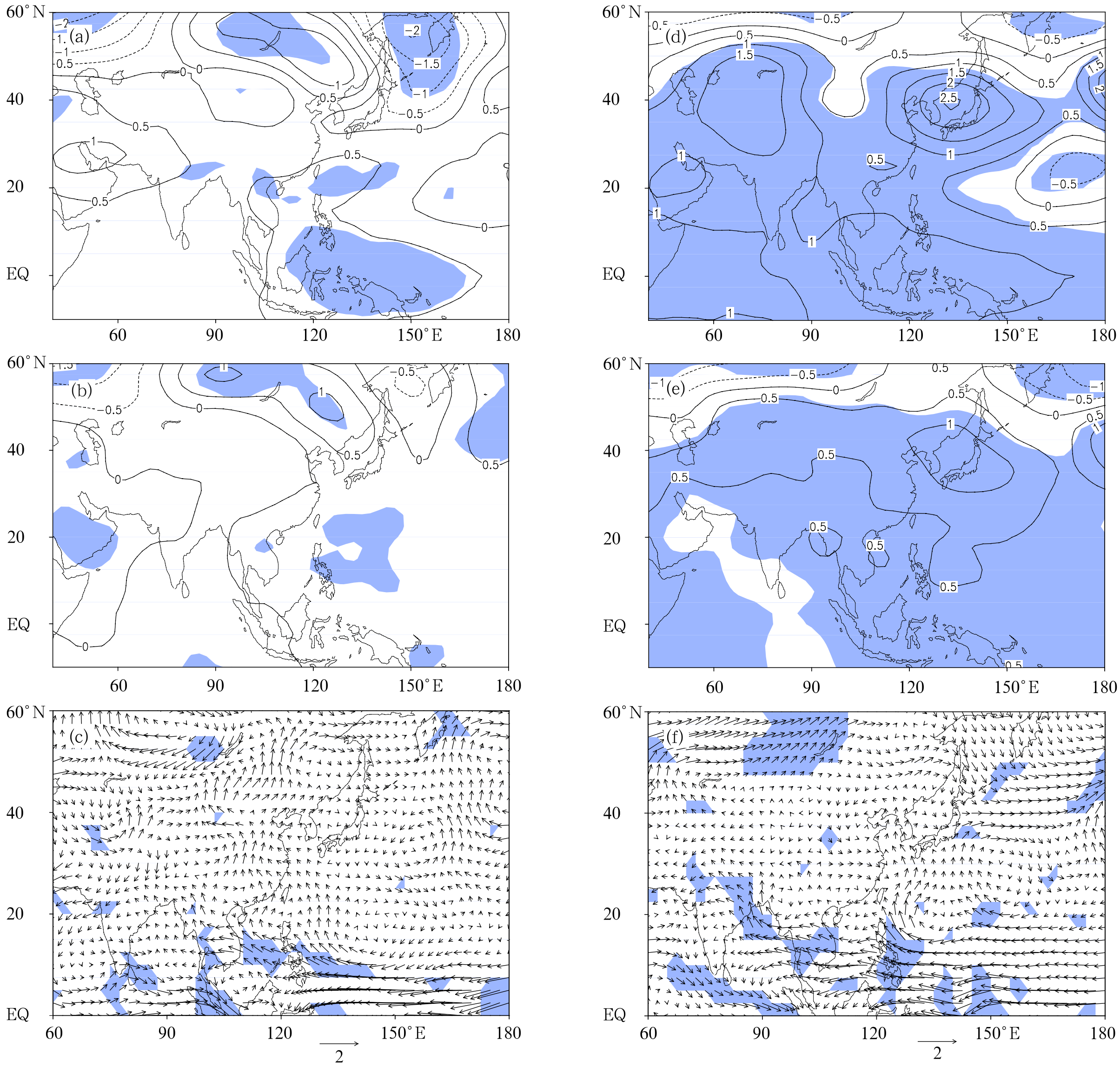

Fig. 8. Composite anomalies of summer 200- (a, d; gpm) and 500-hPa (b, e; gpm) geopotential height, and 850-hPa wind (c, f; m s^{-1}) over East Asia in the following summer of a positive IOD event during (a–c) 1957–1977 and (d–f) 1978–2005. Shadings indicate areas with the 95% confidence level.

South China.

5. Summary

The interdecadal change of the relationship between the IOD mode and the summer climate anomaly in China is documented by using sliding correlation and composite analysis methods based on the monthly precipitation and temperature records at 210 stations in China and the NCEP/NCAR reanalysis data during 1957–2005. The results reveal that such a relationship is robust in some regions, but features interdecadal changes in other regions. The robust relationship manifests mainly in the significant negative correlations between the IOD and the summer precipitation anomaly in the Yangtze River and Yellow River valleys, positive correlations between the IOD and the summer air temperature anomaly in Sichuan, and positive correlations between the IOD and the next summer precipitation anomaly in Sichuan. However, under the interdecadal shift of the large-scale general circulation in the late

1970s, the relationship between the IOD and the summer climate anomaly of China is changed. Before the late 1970s, a developing IOD event tends to decrease summer precipitation in most parts of China and increase temperature in Southwest China, while after the late 1970s, it tends to increase (decrease) precipitation and decrease (increase) temperature in the south (north) of the Yangtze River. During the next summer following a positive IOD event, the precipitation increases in most of China before the late 1970s, while it decreases (increases) in the south (north) of the Yangtze River after the late 1970s. There is no significant correlation between the IOD and the surface air temperature anomaly in most of China in the next summer before the late 1970s. However, the IOD tends to increase the next summer air temperature south of the Yellow River after the late 1970s.

The significant difference in the IOD-related atmospheric circulation anomalies in East Asia between the two interdecadal epoches is responsible for the change of the interannual relationship between the IOD and the summer climate anomaly in China. Before the late 1970s, a developing IOD event tends to enhance the Indian summer monsoon, South China Sea summer monsoon, and East Asian summer monsoon, which leads to less precipitation in South China but more precipitation in western North China. After the late 1970s, a developing IOD event is associated with an enhanced tropical summer monsoon but a weakened East Asian summer monsoon, which results in more precipitation in South China. During the next summer following a positive IOD event, before the late 1970s, southerlies prevail over South China, Hetao area, and Sichuan Province, inducing more precipitation, while after the late 1970s, the South Asian high and the northwestern Pacific subtropical high are stronger and extend westward, causing deficient precipitation in South China.

The interdecadal change of the relationship between the IOD and the summer climate anomaly in China may be influenced by the interdecadal variations of the IOD itself and the East Asian summer monsoon. The global climate system, especially in the Indo-Pacific sector, has experienced a significant interdecadal shift in the late 1970s (Wang, 1995; An and Wang, 2000; Torrence and Webster, 1999; Wang, 2002). Therefore, the interdecadal change of the relationship between the IOD and the summer climate anomaly in China may be closely related to the interdecadal climate variation of the global climate system. The detailed mechanism responsible for these facts revealed in this study needs to be further investigated by using full air-sea coupled general circulation model in the future.

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