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• **Review** •

# Relationship between Indian and East Asian Summer Rainfall Variations

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ABSTRACT

The Indian and East Asian summer monsoons are two components of the whole Asian summer monsoon system. Previous studies have indicated in-phase and out-of-phase variations between Indian and East Asian summer rainfall. The present study reviews the current understanding of the connection between Indian and East Asian summer rainfall. The review covers the relationship of northern China, southern Japan, and South Korean summer rainfall with Indian summer rainfall; the atmospheric circulation anomalies connecting Indian and East Asian summer rainfall variations; the long-term change in the connection between Indian and northern China rainfall and the plausible reasons for the change; and the influence of ENSO on the relationship between Indian and East Asian summer rainfall and its change. While much progress has been made about the relationship between Indian and East Asian summer rainfall variations, there are several remaining issues that need investigation. These include the processes involved in the connection between Indian and East Asian summer rainfall, the non-stationarity of the connection and the plausible reasons, the influences of ENSO on the relationship, the performance of climate models in simulating the relationship between Indian and East Asian summer rainfall, and the relationship between Indian and East Asian rainfall intraseasonal fluctuations.

**Key words**: Indian summer rainfall, East Asian summer rainfall, atmospheric circulation, long-term change, ENSO

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## 1. Introduction

The Indian and East Asian summer monsoons are two components of the whole Asian monsoon system. The Indian summer monsoon is associated with a meridional land–sea thermal contrast reinforced by the thermal effects of the elevated Tibetan Plateau. The East Asian summer monsoon is related to an east–west land–sea thermal contrast that induces a zonal pressure difference between the Asian land mass and the western Pacific Ocean. In association, the two monsoons are related to different circulation systems (Tao and Chen, 1987). The main circulation systems dominating the Indian summer monsoon include the Mascarene high over the South Indian Ocean, the Somali jet, and the westerly over the North Indian Ocean at the lower level, and the Tibetan Plateau and Mascarene highs and associated easterly anomalies over tropical Africa and the Indian Ocean at the upper level (Lau et al., 2000; Wang et al., 2001). The main circulation systems controlling the East Asian summer monsoon include the western Pacific subtropical high, the monsoon trough, the Australian high to the south, and an East Asian trough and upper-level westerly jet to the north (Tao and Chen, 1987; Lau et al., 2000; Wang et al., 2001).

Rainfall is a major element of the summer monsoon. The amount of rainfall in June through September is larger than in the other months and accounts for a major part of total annual rainfall in India, northern China and southern Japan (Fig. 1a). Correspondingly, the rainfall in June through September displays larger year-to-year variability than in the other months in these regions (Fig. 1b). The year-to-year variability of summer rainfall in both India and East Asia is of great concern due to its large societal and economic consequences. Many studies have been conducted to investigate the characteristics of summer rainfall variability and the factors and processes leading to abnormal rainfall over India and East Asia (e.g., Tao and Chen, 1987; Webster et al., 1998; Huang et al., 2003; Yang and Lau, 2004).

In-phase and out-of-phase variations have been detected between Indian and East Asian summer rainfall. For example: the anomalies of Indian and northern China summer rainfall have been found to be positively correlated (Guo and Wang, 1988; Kripalani and Singh, 1993; Zhang et al., 1999; Kripalani and Kulkarni, 2001; Wu, 2002); the summer rainfall in India shows a negative correlation with that in southern Japan (Kripalani and Kulkarni, 2001; Krishnan and Sugi,

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2001; Wu, 2002); an out-of-phase relationship has been reported between Indian and South Korean summer rainfall variations (Kim et al., 2002); and efforts have been made to understand the processes connecting Indian and East Asian summer rainfall variations (Guo and Wang, 1988; Kripalani et al., 1997; Zhang et al., 1999; Krishnan and Sugi, 2001; Kim et al., 2002; Wu, 2002; Wu et al., 2003; Greatbatch et al., 2013).

Analyzing the relationship between summer rainfall variations in India and East Asia and its change may help to unravel the causes of the rainfall variability in these regions. The present paper comprehensively reviews current understanding regarding the relationship between Indian and East Asian summer rainfall variations. The review covers the statistical relationships among different regions in their summer rainfall variations (section 2), the atmospheric circulation pattern linking Indian and East Asian summer rainfall variations (section 3), the non-stationarity of the relationship and the plausible reasons for change in the relationship (section 4), and the influence of ENSO on the relationship between Indian and East Asian summer rainfall and its change (section 5). To close, a discussion on the issues that require further investigation in future research is provided in section 6.

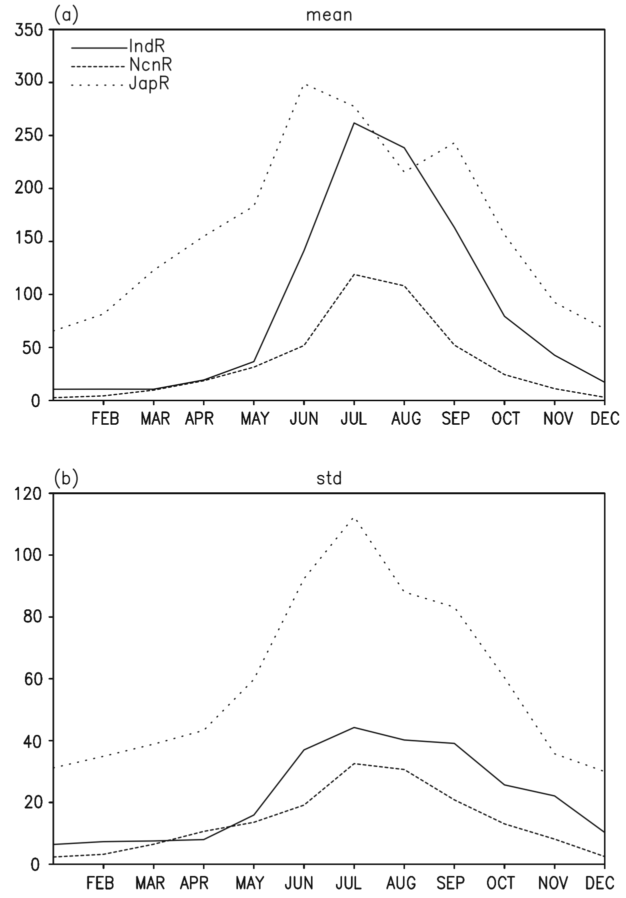

**Fig. 1.** (a) Climatological mean and (b) standard deviation of monthly area-mean Indian rainfall (IndR, solid curve), northern China rainfall (NcnR, dashed curve), and southern Japan rainfall (JapR, dotted curve) based on gridded CRU TS3.23 rainfall data for the period 1901–2014. The domains for obtaining area-mean rainfall are denoted by boxes in Fig. 2. Units: mm month$^{-1}$.

## 2. Statistical relationships among different regions

Although there are differences in the major circulation systems that influence the variability of the Indian and East Asian summer monsoons, some statistical relationships between the summer rainfall variations among Indian and East Asian regions have been identified. For instance, in-phase variation has been detected between summer rainfall in India and northern China (Tao and Chen, 1987; Guo and Wang, 1988; Kripalani and Singh, 1993; Zhang et al., 1999; Kripalani and Kulkarni, 2001; Hu et al., 2005; Liu and Ding, 2008; Greatbatch et al., 2013; Lin et al., 2016). Guo and Wang (1988) analyzed the correlation of China station rainfall with Indian rainfall during June–September (JJAS) for the period 1951–80 and obtained a positive correlation in northern China. This positive relation was confirmed through later analysis of the correlation with respect to Indian or northern China summer rainfall (Kripalani and Singh, 1993; Zhang et al., 1999; Kripalani and Kulkarni, 2001; Wu, 2002; Hu et al., 2005; Wang and Huang, 2006; Liu and Ding, 2008; Greatbatch et al., 2013) and composite analysis of more and less Indian summer rainfall (Liu and Ding, 2008; Lin et al., 2016) for different temporal periods. An EOF analysis of the summer rainfall of both India and China for the period 1951–80 revealed the same sign-loading over India and northern China (Kripalani and Singh, 1993). And Lin et al. (2016) noted that the positive correlation derives mainly from the 2–3-yr interannual component of Indian and northern China summer rainfall variations.

In addition to the correlation between Indian and northern China summer rainfall, a few studies have obtained a negative relationship between Indian and Japan summer rainfall variations (Kripalani and Kulkarni, 2001; Krishnan and Sugi, 2001; Wang et al., 2001; Wu, 2002; Hu et al., 2005; Yun et al., 2014). Based on a composite analysis of wet-minus-dry June–July Baiu years during 1901–94, Krishnan and Sugi (2001) obtained below-normal and above-normal rainfall over northern-central India corresponding to a wet and dry Baiu season, respectively. The correlation of summer rainfall with respect to Indian rainfall displays a contrast between northern China and southern Japan (Kripalani and Kulkarni, 2001; Wu, 2002; Hu et al., 2005). The correlation of summer rainfall with respect to northern China summer rainfall displays negative values over southern Japan (Wang and Huang, 2006). Kim et al. (2002) identified a negative correlation between South Korea and central and northwestern Indian summer rainfall variations based on correlation analysis and SVD for the period 1953–94. Choi et al. (2014) noted a positive correlation between summer rainfall variations in Nepal and South Korea during the period 1981–2010.

The relationship between Indian and East Asian summer rainfall is demonstrated in Fig. 2; specifically, the concurrent correlation of JJAS rainfall with respect to area-mean rainfall for the period 1959–79. The area-mean Indian rainfall is the average over the domain (8°–28°N, 70°–86°E); the area-mean northern China rainfall is the average based on the domain (36°–42°N, 108°–118°E); and the area-mean southern Japan rainfall is the average over the domain (31°–36°N, 130°–140°E). The data source is the gridded monthly dataset of the CRU, University of East Anglia, version TS3.23 (https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_3.23; Harris et al., 2014). The correlation is calculated for the period 1959–79 when the relationship is strong, which will be shown later.

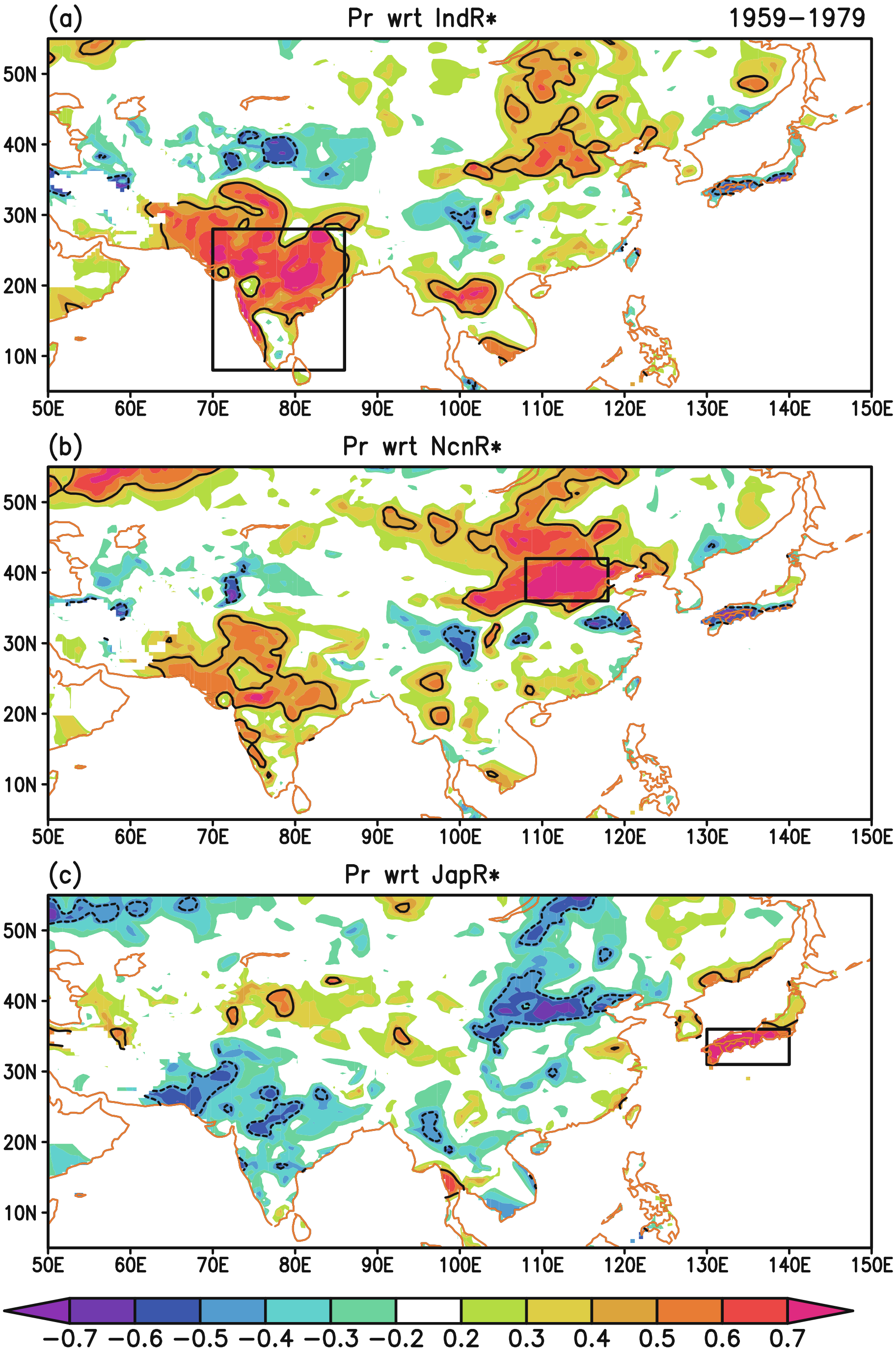

**Fig. 2.** Correlation coefficients of rainfall with respect to area-mean (a) Indian, (b) northern China and (c) southern Japan rainfall during JJAS based on gridded CRU TS3.23 rainfall data for the period 1959–79. The thick lines denote regions where the correlation coefficients are significant at the 95% confidence level according to the Student's *t*-test. The boxes in (a–c) denote the domains for obtaining area-mean Indian, northern China and southern Japan rainfall, respectively.

During this period, with the area-mean Indian rainfall as reference, positive correlation appears over northern China, with the correlation coefficient reaching around 0.5 (Fig. 2a), which is significant at the 99% confidence level according to the Student's *t*-test. Negative correlation is observed over northwestern China and central China. The correlation distribution is similar to earlier studies (e.g., Wang and Huang, 2006; Liu and Ding, 2008; Greatbatch et al., 2013). There is negative correlation over southern Japan, reaching the 95% confidence level. When the correlation is calculated with respect to area-mean northern China rainfall, positive correlation is observed over most of the Indian subcontinent and negative correlation is observed over southern Japan (Fig. 2b). Note that the positive correlation over India is mainly confined to the central and northwestern part. When the correlation is calculated with respect to area-mean southern Japan rainfall, negative correlation is observed over northern China and central and northwestern India (Fig. 2c). Again, the correlation over the Indian peninsular is weak. This indicates that the summer rainfall variations over northern China and southern Japan are mainly associated with those over central and northwestern parts of India.

## 3. Pathways for the connection between Indian and East Asian summer rainfall

The relationship between Indian and East Asian summer rainfall variations operates through atmospheric circulation changes. According to previous studies, there are two plausible pathways for the connection between Indian and East Asian summer rainfall. One is through atmospheric circulation changes over the lower latitudes, and the other is via atmospheric circulation changes over the midlatitudes of Asia. Here, for brevity, the two pathways are referred to as the south and north pathways, respectively.

In the south pathway, the moisture transport to East Asia is modified by anomalous winds associated with the Indian summer monsoon (Zhang, 1999; 2001; Liu and Ding, 2008). Based on correlation and composite analysis with respect to area-mean vertically integrated tropospheric water vapor transport over the region (0°–20°N, 80°–100°E) for the period 1951–98, Zhang (2001) showed that strong (weak) water vapor transport from the Indian monsoon region is accompanied by less (more) water vapor transport over East Asia, leading to less (more) rainfall over the middle and lower reaches of the Yangtze River valley. On the other hand, the water vapor transport over northern China has a positive correlation with that from the Indian monsoon region (Zhang, 1999). Liu and Ding (2008) identified stronger (weaker) northward water vapor transport over East Asia corresponding to more (less) Indian summer rainfall, favorable for more (less) rainfall over northern China. These results explain the positive relationship between Indian and northern China summer rainfall variations.

The south pathway involves an anomalous high over the subtropical western North Pacific (Krishnan and Sugi, 2001; Zhang, 2001). One possible interpretation is that the anomalous heating associated with Indian summer rainfall anomalies modifies the atmospheric circulation over the western North Pacific, which in turn influences East Asia through atmospheric teleconnection (Lau et al., 2000; Krishnan and Sugi, 2001; Wang et al., 2001). However, the relationship between change in the western North Pacific subtropical high and the Indian summer monsoon differs among studies depending on the monsoon index used (e.g., Lau et al., 2000; Wang et al., 2001).

The north pathway involves a zonal wave pattern in the middle and upper troposphere over the midlatitudes of Asia. The wave pattern has been identified in many previous studies (Guo and Wang, 1988; Kripalani et al., 1997; Lau et al., 2000; Krishnan and Sugi, 2001; Wang et al., 2001; Kim et al., 2002; Lu et al., 2002; Wu, 2002; Wu et al., 2003; Hu et al., 2005; Liu and Ding, 2008; Greatbatch et al., 2013; Lin et al., 2016). Corresponding to above-normal Indian rainfall, anomalous anticyclones are identified northwest of the Tibetan Plateau and over Northeast China (Guo and Wang, 1988; Krishnan and Sugi, 2001; Wu, 2002; Hu et al., 2005; Greatbatch et al., 2013; Lin et al., 2016). An atmospheric circulation anomaly pattern over the midlatitudes of Asia can be obtained through composite analysis based on June–July rainfall in Japan (Krishnan and Sugi, 2001). This pattern, consisting of an anomalous low over the Caspian Sea and Aral Sea region, a high over Mongolia, and an anomalous low over Korea and Japan, was termed the "Asian continent pattern" in Krishnan and Sugi (2001). In upper-level meridional wind fields, alternate positive and negative anomalies are very prominent along the westerly jet stream over the midlatitudes of Asia (Lu et al., 2002), which is termed the "Silk Road Pattern" (Enomoto et al., 2003). Such a wave pattern is strong when Indian and northern China rainfall anomalies are of the same sign, but weak when they are opposite in sign (Lin et al., 2016). Correlation analysis carried out by Kripalani et al. (1997) also indicates the presence of such a wave pattern on intraseasonal time scales. The composite 200-hPa wind anomalies during the Indian monsoon break phase display a similar wave pattern (Krishnan et al., 2000).

Using EOF analysis, Wu (2002) showed that this wave pattern is a dominant atmospheric circulation pattern at the upper level over the midlatitudes of continental Asia during boreal summer. The pattern is composed of two parts: a zonally uniform variation and a zonal wave-type variation. As such, it does not possess a pure wave-type or dipole structure. The pattern correlates positively with summer rainfall in India and northern China, and negatively with summer rainfall in southern Japan. Thus, the pattern plays an important role in connecting the summer rainfall variations in India to those in northern China and southern Japan. This wave pattern forms the most prominent part of the so-called "circumglobal teleconnection pattern" (Ding and Wang, 2005).

Previous studies have identified an east–west shift of the South Asian high associated with anomalous Indian heating (Kim et al., 2002; Wei et al., 2014, 2015; Choi et al., 2016). Such a shift in the location of the South Asian high is part of the signal related to the above wave pattern. It is shown that the east–west shift of the South Asian high induced by condensational latent heat anomalies over northern India affects the summer rainfall over the middle and lower reaches of the Yangtze River valley and southern China (Wei et al., 2014; 2015), and over Korea (Choi et al., 2016).

The wave pattern over the midlatitudes of Asia appears to be partly contributed by anomalous heating associated with anomalous Indian summer rainfall. This is implied by the baroclinic structure of circulation anomalies associated with anomalous Indian rainfall (Wu, 2002). Rodwell and Hoskins (1996) suggested a role of Indian monsoon heating in inducing an anticyclone northwest of the Tibetan Plateau through the linear Gill-type Rossby-wave response. After the midlatitude westerly is perturbed, downstream East Asia can be affected through Rossby wave propagation (Wu and Wang, 2002). Such wave propagation is camouflaged by the presence of the zonally uniform part of the anomalies. When the zonal-mean part of anomalies is removed from the 200-hPa height anomalies, the wave pattern becomes very clear along 30°–60°N (Wu, 2002). The calculated wave activity flux in the upper troposphere displays divergence west of the Tibetan Plateau, indicative of the forcing of anomalous Indian heating (Wu and Wang, 2002; Wu et al., 2003; Hu et al., 2005). The role of anomalous Indian heating in the development of the wave pattern has been confirmed by model experiments (Wu et al., 2003; Liu and Ding, 2008; Greatbatch et al., 2013). With anomalous heating specified over the Indian subcontinent, simulations with both a baroclinic model and an AGCM reproduce the observed wave pattern over the midlatitudes of Asia (Greatbatch et al., 2013).

The atmospheric circulation pattern associated with the Indian summer rainfall anomaly is shown in Figs. 3a and 4a, which display the wind anomalies at 850 hPa and 200 hPa obtained by regression with respect to area-mean JJAS Indian rainfall anomalies for the period 1959–79. The atmospheric wind data are based on the NCEP–NCAR reanalysis dataset (Kalnay et al., 1996). At the lower level, an anomalous cyclone is observed over the southern Arabian peninsula, the Arabian Sea, and India (Fig. 3a). At the upper level, an anomalous anticyclone is observed, centered over the northwest of the Tibetan Plateau (Fig. 4a). This indicates a Rossby wave–type response to anomalous heating over the Indian region (Rodwell and Hoskins, 1996; Wu, 2002). Over East Asia, anomalously southerly winds are observed at the lower level over eastern China (Fig. 3a), which bring more moist air from lower latitudes to northern China, favoring more rainfall there. An anomalous anticyclone covers Northeast China, Korea and the Japan Sea at the upper level (Fig. 4a). Similar atmospheric wind anomaly patterns are obtained corresponding to area-mean JJAS northern China rainfall anomalies (Figs. 3b and 4b). A generally similar distribution of wind anomalies appears corresponding to area-mean JJAS southern Japan rainfall anomalies, except for an opposite sign (Figs. 3c and 4c). In comparison, the lower-level southwesterly wind anomalies over Japan are stronger corresponding to southern Japan rainfall than to Indian and northern China rainfall (Fig. 3c versus Figs. 3a and b).

The role of the north pathway in the connection between Indian and East Asian summer rainfall variations is summarized schematically in Fig. 5. Above-normal Indian rainfall is accompanied by anomalous heating, an anomalous lower-level low over the northern Arabian Sea and continental India, and an anomalous upper-level high over central Asia. The perturbed upper-level height is followed by a wave pattern over the midlatitudes of continental Asia, with an anomalous low southwest of Lake Baikal and an anomalous high over Northeast China, Korea and the Japan Sea. At the lower level over East Asia, an anomalous low and an anomalous high form over Mongolia and the Japan Sea, respectively. East of the anomalous low, anomalous lower-level southerly winds blow over eastern China, bringing more moist air from lower latitudes and inducing anomalous lower-level convergence and anomalous ascent, favoring more rainfall in northern China. Under the influence of the anomalous high, anomalous descent develops over southern Japan, suppressing rainfall there. This leads to same-sign rainfall anomalies in India and northern China, but opposite-sign rainfall anomalies in India/northern China and southern Japan.

## 4. Non-stationarity of the relationship and plausible reasons

Analysis shows that the relationship between Indian and East Asian summer rainfall variations has experienced long-term changes. Guo (1992) pointed out that the correlation between Indian and northern China summer rainfall variation was weak during 1921–50, but strong during 1891–1920 and 1951–80. The long-term change in the correlation between Indian and northern China rainfall was obtained in later studies too (Kripalani and Kulkarni, 2001; Wu, 2002; Wu and Wang, 2002; Wang and Huang, 2006). The correlation coefficient between Indian and northern China rainfall can exceed 0.70 for the period 1945–74, but is −0.30 for 1827–56 (Wang and Huang, 2006). Kripalani and Kulkarni (2001) also detected a long-term change in the correlation between Indian–Japan and northern China–Japan summer rainfall. The three pairs of correlations are strong for the 1960s and 1970s, but weakened during the 1980s (Kripalani and Kulkarni, 2001). Yun et al. (2014) pointed out a recent intensification in the difference of convective precipitation between the South Asian monsoon and East Asian monsoon systems during June–July.

But what are the plausible reasons for the long-term changes in the relationship between Indian and East Asian summer rainfall? Evidence suggests there could be many, including: change in the dominant circulation anomaly pattern over the midlatitudes of Asia, which may modify the distribution of summer rainfall anomalies over East Asia (Wu, 2002; Wu and Wang, 2002; Lin et al., 2016); change in the connection between anomalous Indian heating and the circulation anomaly pattern (Wu, 2002; Wu and Wang, 2002); and change in the impacts of other factors affecting Indian and East Asian summer rainfall variability (Hu et al., 2005; Wang and Huang, 2006). Wang and Huang (2006) indicated that

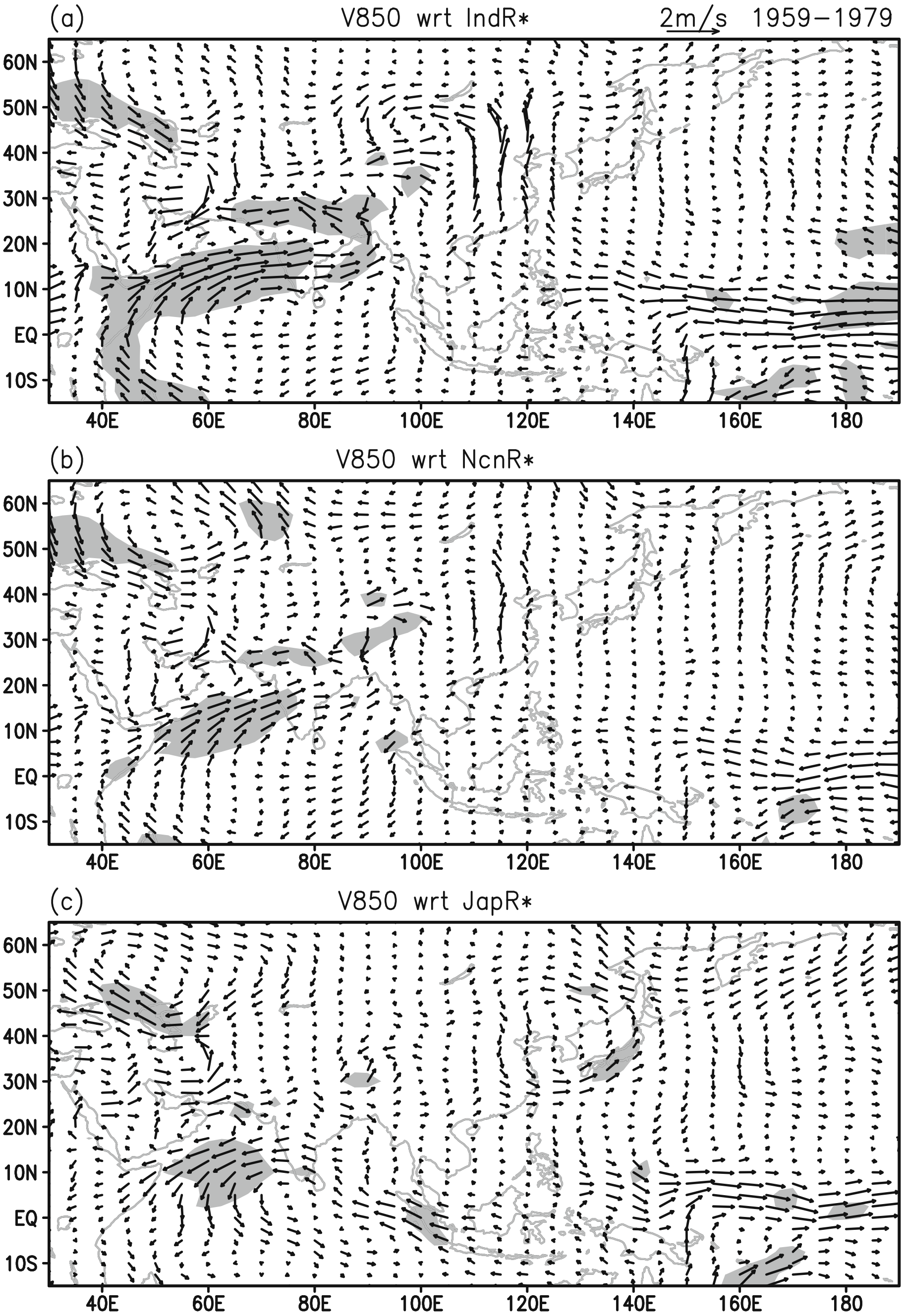

**Fig. 3.** Anomalies (units: m s$^{-1}$) of 850-hPa winds obtained by regression with respect to normalized area-mean (a) Indian, (b) northern China and (c) southern Japan rainfall during JJAS based on gridded CRU TS3.23 rainfall data and NCEP–NCAR reanalysis wind data for the period 1959–79. Shading denotes regions where wind anomalies are significant at the 95% confidence level according to the Student's *t*-test. The scale for wind vectors is displayed in the top-right corner.

the correlation between Indian and northern China rainfall is high when the mean rainfall is large in the two regions, and vice versa.

The weakened relationship between Indian and northern China summer rainfall around the late 1970s may have been contributed by both change in the midlatitude Asian wave pattern and change in the influence of anomalous Indian heating on the wave pattern (Wu, 2002; Wu and Wang, 2002). The East Asian anomalous anticyclone displays a southeastward shift after the late 1970s (Wu, 2002), and this results in a change in the distribution of associated summer rainfall anomalies in East Asia. Meanwhile, the West Asian anomalous anticyclone displaces northeastward after the late 1970s (Wu, 2002), and this may have weakened its connection to anomalous Indian heating. Further, the distribution of large rainfall variability in India shifted to lower latitudes after the

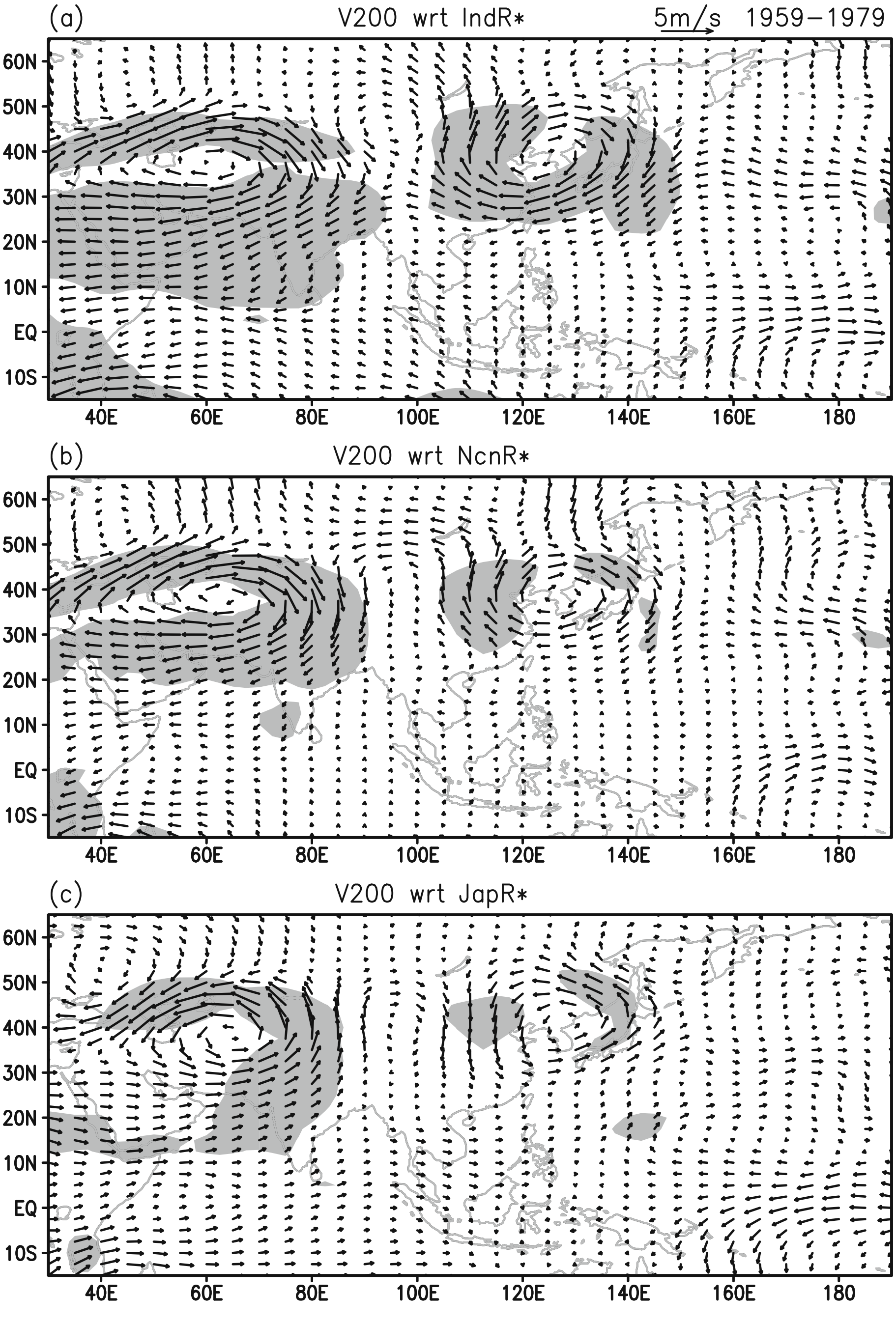

**Fig. 4.** As in Fig. 3 except for 200-hPa winds.

late 1970s (Wu, 2002; Wu and Wang, 2002). As the atmospheric response depends upon the location of anomalous heating (Rodwell and Hoskins, 1996), such a shift weakened the impacts of anomalous Indian heating on the midlatitude Asian atmospheric circulation (Wu and Wang, 2002). Together, these changes resulted in a weakening of the statistical relationship between Indian and northern China summer rainfall variations after the late 1970s.

Lin et al. (2016) indicated that when the anomalous high over the Iranian Plateau shifts westward, the circumglobal teleconnection pattern cannot form. In such a case, northern China summer rainfall is mainly affected by the atmospheric circulation pattern over East Asia and the western Pacific, and thus its relationship with Indian summer rainfall is weakened or even becomes opposite. Wu and Wang (2002) showed that the anomalous cyclone over Northeast China during El Niño decaying summers was contributed by both anomalous Indian and western North Pacific heating before the late 1970s, whereas it was mainly associated with anomalous western North Pacific heating located at higher latitudes after the late 1970s. This led to a shift in the location of the anomalous cyclone.

Yun et al. (2014) proposed that the recent strengthening of the zonal gradient of SST in the tropical Indo-Pacific Ocean is a possible cause for the intensified contrast of convective precipitation between the South and East Asian monsoons. The

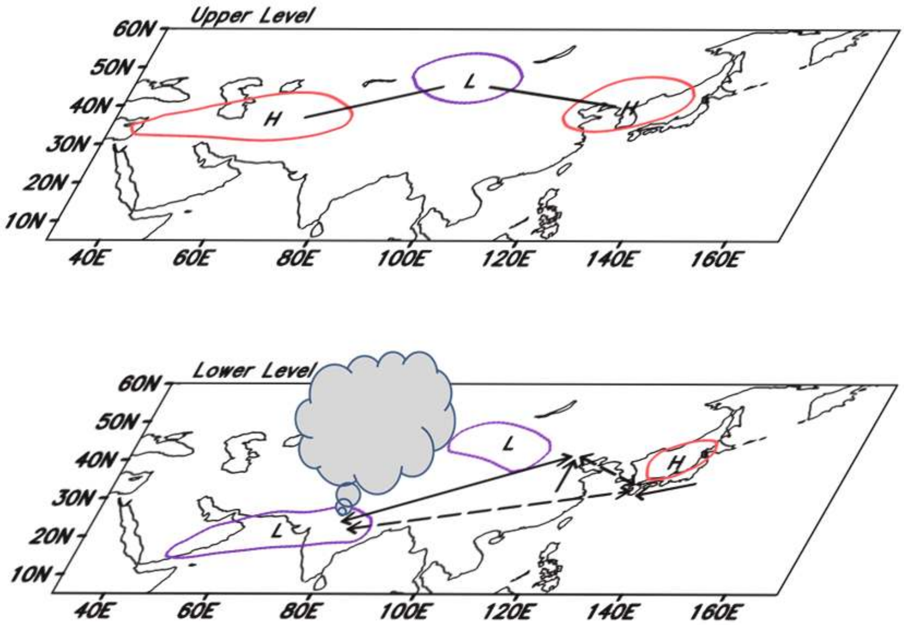

**Fig. 5.** Schematic representation of the connection between Indian and East Asian summer rainfall variations. Red contours with "H" denote anomalous highs, and purple contours with "L" denote anomalous lows. Solid and dashed lines with double arrows denote same-sign and opposite-sign rainfall variations, respectively. Lines with one arrow denote anomalous wind. Lines without arrows denote the wave pattern. The cloud shape denotes anomalous heating.

strengthening of the zonal SST gradient enhanced convection over the Maritime Continent, facilitating the northwestward emanation of Rossby waves. Consequently, a cyclonic circulation anomaly formed over the South Asian monsoon region, leading to more rainfall there. The cyclonic anomaly changed the local Hadley circulation, forming a strong meridional height gradient pattern along the upper-level Asian jet stream, suppressing rainfall over East China–Japan. This contributed to the enhanced contrast between South and East Asian summer rainfall anomalies. A recent study by Preethi et al. (2016) showed that the summer rainfall over northern India and northern China, and the recent decreasing rainfall trends over these regions, are related to SST changes in the western Indian Ocean; whereas, the rainfall variations over South India and South China and the recent increasing trends over these regions are related to SST changes in the western Pacific Ocean.

The long-term change in the correlation between Indian and East Asian summer rainfall is demonstrated in Fig. 6 using updated CRU rainfall data. The 21-year sliding correlation is calculated between different pairs of time series to show the change in the correlation. Apparently, the cor-

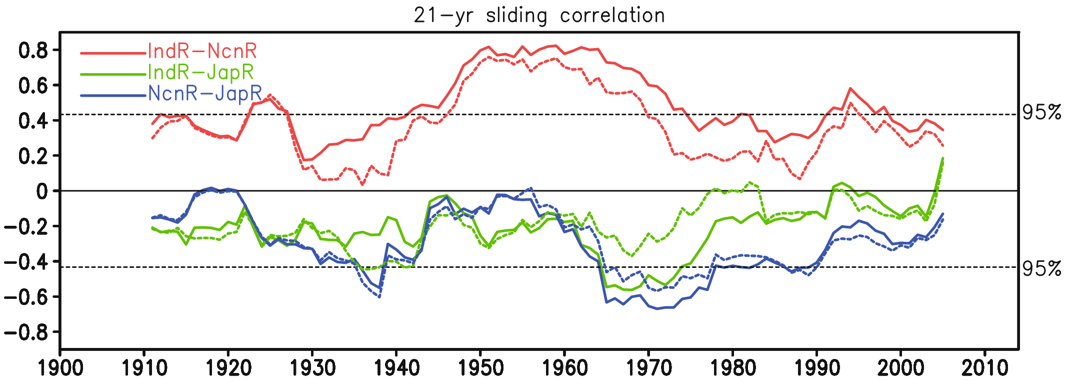

**Fig. 6.** 21-year sliding correlation between area-mean JJAS Indian and northern China rainfall (red curves), between area-mean JJAS Indian and southern Japan rainfall (green curves), and between area-mean JJAS northern China and southern Japan rainfall (blue curves). Solid curves denote the correlation coefficient when the ENSO signal is not removed, and dashed curves denote the correlation coefficient after the ENSO signal is removed, based on partial correlation. Horizontal dashed lines denote the 95% confidence level of the correlation coefficient according to the Student's *t*-test.

relation between Indian and northern China summer rainfall is strong for the late 1940s through to the early 1970s; whereas, the correlation is weak during the 1930s and early 1980s through to the 1990s. The results are consistent with previous studies (Guo, 1992; Kripalani and Kulkarni, 2001; Wu, 2002; Wang and Huang, 2006). In addition, the correlation between Indian and southern Japan summer rainfall is strongly negative around 1970, as is that between northern China and southern Japan rainfall; whereas, these two correlations are weaker during the 1990s. These results are consistent with Kripalani and Kulkarni (2001). Note that 1959–79 is a time period when the three pairs of correlations are large and significant, and is thus selected to demonstrate the relationship between Indian and East Asian summer rainfall in Fig. 2. Note that the correlation between Indian and southern Japan rainfall is insignificant, except for a short period around 1970.

It is important to highlight that the above-mentioned studies included the time period 1951–80 when analyzing the correlation between East Asian summer rainfall and Indian rainfall. That is why these studies obtained a significant relationship. For comparison, we show in Fig. 7 the correlation

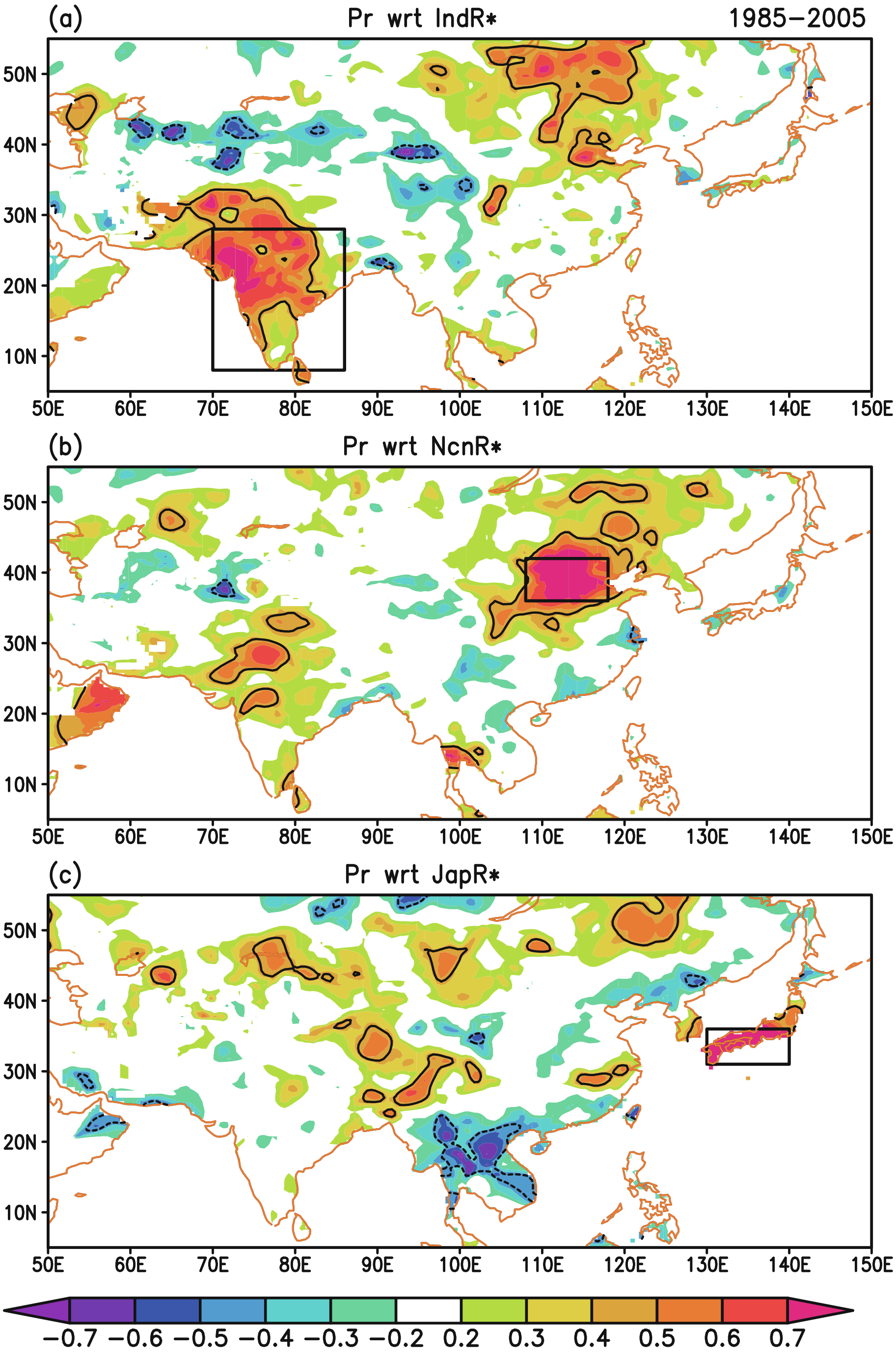

**Fig. 7.** As in Fig. 2 except for the period 1985–2005.

during 1985–2005, when the three correlations are weaker (Fig. 6) compared to the period 1959–79. When taking the JJAS Indian rainfall as reference, the correlation in northern China is weaker (Fig. 7a) compared to the period 1959–79. The correlation in southern Japan is low. With JJAS northern China rainfall as reference, the positive correlation in India is confined to the northwestern part (Fig. 7b), and there is no obvious correlation in Japan. When taking JJAS southern Japan rainfall as reference, the correlation is weak in both India and northern China (Fig. 7c). The above results indicate that the summer rainfall variations in India, northern China and southern Japan possess low coherence during the period 1985–2005.

## 5. Influence of ENSO

As both Indian and East Asian summer rainfall are modulated by ENSO (e.g., Kripalani and Kulkarni, 1997; Webster et al., 1998; Wang et al., 2001; Wu et al., 2003), this phenomenon may contribute to the relationship between Indian and East Asian rainfall variations. Furthermore, the impact of ENSO on Asian summer rainfall may be modulated by decadal and multi-decadal variability (e.g., Kripalani and Kulkarni, 1997; Feng et al., 2014). For example, the impact of El Niño (La Niña) on Indian monsoon rainfall is greater during below-normal (above-normal) rainfall regimes (Kripalani and Kulkarni, 1997).

By separating the ENSO-related and ENSO-independent components of Indian summer rainfall, Hu et al. (2005) investigated the role of ENSO in the connection between the summer rainfall variations of India and East Asia. They indicated that ENSO generally reinforces the connection between Indian and East Asian summer rainfall variations. The ENSO-related part affects East Asian summer rainfall variations through two meridional teleconnection patterns: one over continental East Asia, and the other over the western Pacific Ocean. The ENSO-independent part influences East Asian summer rainfall variations via a zonal pattern over the midlatitudes of continental Asia.

Wang and Huang (2006) suggested a contribution from ENSO to the secular variation in the correlation between Indian and northern China summer rainfall, with a weakened connection corresponding to a weakened influence of ENSO on both Indian and northern China rainfall variations. They noted that the relationship is related to the frequency of occurrence of La Niña events. When the equatorial eastern Pacific SST is low, the frequency of occurrence of La Niña events increases and the relationship between Indian and northern China rainfall is strong. In contrast, when there are fewer La Niña events, the relationship is weak.

The influence of ENSO is examined by comparing the correlation between Indian and East Asian summer rainfall, with and without the ENSO signal, through partial correlation analysis. The ENSO signal is represented by the JJAS Niño3.4 (5°S–5°N, 170°–120°W) SST anomaly, constructed using the SST data from HadISST1.1 (Rayner et al., 2003). After the ENSO signal is removed, the correlation between Indian and northern China rainfall becomes weaker during most of the analysis period (Fig. 6). The correlation between Indian and southern Japan rainfall becomes smaller during the mid-1960s through to the 1970s, but experiences little change during the other periods. The correlation between northern China and southern Japan rainfall is weaker during the 1960s through to the early 1980s, and the change is negligible during the other periods. Thus, ENSO enhances the three pairs of correlations during some periods. It also contributes to the changes in the correlation between Indian and southern Japan rainfall variations, as well as those between northern China and southern Japan, during the 1960s and early 1980s. In particular, the correlation between Indian and southern Japan rainfall becomes insignificant in almost all periods after removing the effect of ENSO. Nevertheless, the change in the correlation between Indian and northern China rainfall remains clear around the late 1970s after the ENSO signal is removed. This indicates that the contribution of the impacts of ENSO to the long-term change in the relationship between Indian and northern China rainfall may be small.

## 6. Issues

The present paper reviews current understanding regarding the relationship between Indian and East Asian summer rainfall variations. Based on the review, there are several issues remaining that need to be investigated in future research. Five of these issues are discussed here. It is hoped that this may promote further studies on the relationship between the variabilities of the Indian and East Asian summer monsoons.

The first issue relates to the processes involved in the connection between the summer rainfall variations among Indian and East Asian monsoon regions. Previous studies identified two pathways (referred to here as the south and north pathways) for the connection, but what are the relative roles of these pathways in the connection between Indian and East Asian rainfall? The south pathway may be more important in linking Indian rainfall to the rainfall variability over the Yangtze River and southern regions of Japan. Whereas, the north pathway may play a more important role in linking Indian rainfall to the rainfall variability of northern China. The south pathway includes a link between Indian heating and western Pacific circulation change, which needs to be clarified.

The second issue is surrounding the non-stationary of the relationship between Indian and East Asian rainfall and the plausible reasons. The long-term change displays some differences among the three pairs of correlations, indicative of different reasons. The relationship between Indian and northern China rainfall change may be relevant to the midlatitude wave pattern change. It remains to be investigated what may have contributed to the wave pattern change. How the change in the lower-latitude circulation pattern may contribute to the relationship between Indian and southern Japan rainfall change is not yet clear.

The third issue is the influence of ENSO and regional SST anomalies on the connection between Indian and East Asian summer rainfall and its change. Questions remain as to how the change in ENSO characteristics (amplitude and evolution) in the past may have contributed to the change in the relationship between Indian and East Asian summer rainfall. Previous studies have indicated a role played by regional SST anomalies in atmospheric circulation changes over Asia and the western North Pacific. However, the nature of the roles played by regional SST anomalies in the change in the relationship between Indian and East Asian rainfall needs to be investigated.

The fourth issue revolves around the relationship between Indian and East Asian summer rainfall in climate models. It is necessary to evaluate the performance of climate model simulations in this regard. The use of ensemble model simulations may help to identify the processes contributing to the relationship and its change in climate models. How the internal variability contributes to the change in the relationship between Indian and East Asian summer rainfall, and to what extent external forcing may play a role in modulating the connection, are questions worthy of investigation.

Finally, the fifth issue is the connection between Indian and East Asian summer rainfall on intraseasonal timescales. The propagation of intraseasonal signals in the tropics may play a role in the relationship between Indian and western North Pacific–East Asia intraseasonal rainfall variations (e.g., Lau and Chan, 1986; Kripalani et al., 1991). The midlatitude Asian wave pattern on intraseasonal timescales and its relationship with the intraseasonal variability of the Indian monsoon has been noted in previous studies (e.g., Kripalani et al., 1997; Krishnan et al., 2000). But does this wave pattern play a role in linking the active and break phases of the Indian summer monsoon to intraseasonal fluctuations in northern China rainfall? This issue is relevant to intraseasonal climate prediction over East Asia.

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