Perspectives on the non-stationarity of the relationship between Indian and East Asian summer rainfall variations

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\textbf{ABSTRACT}

The relationship between Indian and East Asian summer rainfall variations is non-stationary in observations as well as in historical simulations of climate models. Is this non-stationarity due to changes in effects of external forcing or internal atmospheric processes? Whilst ENSO is an important oceanic forcing of Indian and East Asian summer rainfall variations, its impacts cannot explain the observed long-term changes in the Indian–East Asian summer rainfall relationship. Monte Carlo test indicates that the role of random processes cannot be totally excluded in the observed long-term changes of the relationship. Analysis of climate model outputs shows that the Indian–North China summer rainfall relationship displays obvious temporal variations in both individual and ensemble mean model simulations and large differences among model simulations. This suggests an important role played by atmospheric internal variability in changes of the Indian–East Asian summer rainfall relationship. This point of view is supported by results from a 100-years AGCM simulation with climatological SST specified in the global ocean. The correlation between Indian and North China or southern Japan summer rainfall variations displays large fluctuations in the AGCM simulation.

\textbf{1. Introduction}

Given the high demand for water supply in the populous countries of South and East Asia, the variability and prediction of summer rainfall in these regions has long been of great concern. Previous studies have led to important progress in understanding the factors and processes involved in the year-to-year summer rainfall variations of South and East Asia (e.g. Webster et al. 1998). One important factor is ENSO, which imposes a substantial impact on both Indian and East Asian summer rainfall variability (e.g. Walker 1923; Huang and Wu 1989; Wang, Wu, and Lau 2001; Wu, Hu, and Kirtman 2003).

The connection between the variations of Indian and East Asian summer rainfall is also a focus in the literature. Previous studies have revealed an in-phase relationship in the summer rainfall variations between India and North China (Guo and Wang 1988; Kripalani and Singh 1993; Zhang, Sumi, and Kimoto 1999; Kripalani and Kulkarni 2001; Wu 2002; Liu and Ding 2008; Greatbatch, Sun, and Yang 2013; Preethi et al. 2017a), and an out-of-phase relationship between India and southern Japan (Kripalani and Kulkarni 2001; Krishnan and Sugi 2001; Wang, Wu, and Lau 2001; Wu 2002; Yun, Lee, and Ha 2014) or South Korea (Kim et al. 2002; Preethi et al. 2017a). According to the literature, there are two pathways for the connection between Indian and East Asian summer rainfall variations, as summarized by Wu (2017). One pathway is atmospheric circulation change over the lower latitudes that modifies the moisture transport from the Indian Ocean to East Asia (Zhang, Sumi, and Kimoto 1999; Krishnan and...
Sugi 2001; Zhang 2001; Liu and Ding 2008). The other pathway is atmospheric circulation change over the mid-latitudes of continental Asia, featuring a zonal wave pattern (Guo and Wang 1988; Kripalani, Kulkarni, and Singh 1997; Krishnan and Sugi 2001; Wang, Wu, and Lau 2001; Kim et al. 2002; Lu, Oh, and Kim 2002; Wu 2002; Enomoto, Hoskins, and Matsuda 2003). This zonal wave pattern is partly associated with anomalous Indian heating, and in turn modulates winds over East Asia (Wu 2002; Wu, Hu, and Kirtman 2003; Ding and Wang 2005; Liu and Ding 2008; Greatbatch, Sun, and Yang 2013).

A key issue is that the relationship between the variations of Indian and East Asian summer rainfall is not steady. Long-term changes in the relationship have been identified in previous studies (Guo 1992; Kripalani and Kulkarni 2001; Wu 2002; Wang and Huang 2006; Lin, Lu, and Wu 2017; Ha et al. 2017; Preethi et al. 2017b). One prominent change in the Indian–North China summer rainfall relationship occurred around the late 1970s (Wu 2002). The weakened connection after the late 1970s can be attributed to a shift in the distribution of large rainfall variability in India to lower latitudes, which weakened the impacts of anomalous Indian heating on the midlatitude Asian atmospheric circulation (Wu 2002; Wu and Wang 2002). The change in the relationship has also been detected in coupled climate model simulations (Preethi et al. 2017b; Wu and Jiao 2017). However, a plausible explanation for the non-stationarity in the above relationship has yet to be determined. The present study discusses various perspectives of the long-term changes in the connection between the summer rainfall variations of India and East Asia.

Following this introduction, we begin by showing the long-term changes in the Indian–East Asian summer rainfall relationship in observations and climate model simulations (Section 2). Then, we present different perspectives on what may contribute to the long-term changes in the relationship (Section 3). Lastly, some concluding remarks are provided (Section 4).

2. Long-term changes in the relationship

The long-term change in the relationship between Indian and North China summer rainfall variations in observations has been identified in previous studies. Guo (1992) pointed out that the Indian–North China summer rainfall correlation is weak during 1921–1950 but strong during 1891–1920 and 1951–1980. A change in the Indian–North China summer rainfall relationship around the late 1970s was noted by Kripalani and Kulkarni (2001), Wu (2002), and Wang and Huang (2006). Long-term changes in the Indian–southern Japan and North China–southern Japan summer rainfall correlation were identified by Kripalani and Kulkarni (2001). The above changes in the Indian–East Asian summer rainfall relationship have been confirmed by Wu (2017) and Wu and Jiao (2017) using updated rainfall data. Secular changes have been observed in the relationship between the Indian and Yangtze–Huai River summer rainfall variations, as well as between the Indian and Korea–Japan summer rainfall variations (Ha et al. 2017b; Preethi et al. 2017b).

The long-term changes in the Indian–East Asian summer rainfall relationship are illustrated in Figure 1(a), which shows three correlations in a 21-years sliding window using GPCC version 7 0.5° gridded rainfall data (Schneider et al. 2015). Following Wu (2017) and Wu and Jiao (2017), the domains for calculating the area-mean Indian, North China, and southern Japan rainfall are (8°–28°N, 70°–86°E), (36°–42°N, 108°–118°E), and (31°–36°N, 130°–140°E), respectively. Apparently, the Indian–North China June–September (JJAS) rainfall correlation is higher during 1950s–1960s than during the 1980s and 1930s, which is consistent with previous studies (Kripalani and Kulkarni 2001; Wu 2002). The Indian–southern Japan and North China–southern Japan JJAS rainfall correlation is higher around 1970 than during the 1950s and 1990s. The results agree with Wu (2017) and Wu and Jiao (2017), whose studies used different rainfall data over land.

Long-term changes in the Indian–North China summer rainfall relationship have been identified in the historical simulations of the CMIP5 climate models (Wu and Jiao 2017). Furthermore, there are also secular variations in the relationship between Indian and Korea–Japan summer rainfall variations in historical simulations and future projections of climate models (Preethi et al. 2017b), albeit with the timing of the changes in the relationship differing from model to model and among different simulations of a single model (Wu and Jiao 2017). As an illustration, Figure 2 displays the 21-years running correlation between Indian and North China JJAS rainfall in two members of the CCSM4 and CNRM-CM5 simulations, which are selected from all the simulations shown in Wu and Jiao (2017). In the two members of the CCSM4 simulations, opposite correlation appears around 1980 (Figure 2(a)). In the two members of the CNRM-CM5 simulations, the correlation is opposite in the 1980s but tends to vary in-phase before the 1960s (Figure 2(b)). The range of change in the correlation coefficient is large in the two members, from above +0.4 to below –0.4.

3. Perspectives on the factors involved in the changes in the relationship

There may be many reasons behind the long-term changes in the Indian–East Asian summer rainfall relationship. Here, we discuss four of them.
Given the impact of ENSO on both Indian and East Asian summer monsoon variability (Wang, Wu, and Lau 2001), ENSO is likely a factor involved in the long-term changes in the Indian–East Asian summer rainfall relationship through changes its impacts on either the Indian or East Asian summer monsoon (Kumar, Rajagopalan, and Cane 1999; Wu and Wang 2002). Hu et al. (2005) indicated that ENSO may reinforce the connection between Indian and North China summer rainfall variations. Wang and Huang (2006) noted that a weakened connection may correspond to weakened influences of ENSO on both Indian and North China rainfall variations. In addition, SST anomalies in other regions may affect the relationship. E.g. Yun, Lee, and Ha (2014) proposed that a strengthened zonal gradient of SST between the Indian Ocean, western Pacific, and eastern Pacific may be a possible cause of an enhanced contrast in convective precipitation between South Asia and East Asia. Lee et al. (2017) suggested an enhanced influence of tropical Atlantic SSTs on Korean summer rainfall variations since the mid-1970s.

Interdecadal changes in the relationships among Indian, North China, and southern Japan summer rainfall variations remain after ENSO-related signals have been removed (Wu 2017; Wu and Jiao 2017) – a point clearly demonstrated by comparing Figure 1(b) with Figure 1(a). In Figure 1(b), the impacts of the ENSO signal on the correlation have been removed through partial correlation with respect to JJA Niño3.4 (5°S–5°N, 170°–120°W) SST anomalies based on HadISST1.1 data (Rayner et al. 2003). Note: The horizontal dashed lines denote the 95% confidence level of the correlation coefficient according to the Student’s t-test.

### 3.1. ENSO

Given the impact of ENSO on both Indian and East Asian summer monsoon variability (Wang, Wu, and Lau 2001), ENSO is likely a factor involved in the long-term changes in the Indian–East Asian summer rainfall relationship through changes its impacts on either the Indian or East Asian summer monsoon (Kumar, Rajagopalan, and Cane 1999; Wu and Wang 2002). Hu et al. (2005) indicated that ENSO may reinforce the connection between Indian and North China summer rainfall variations. Wang and Huang (2006) noted that a weakened connection may correspond to weakened influences of ENSO on both Indian and North China rainfall variations. In addition, SST anomalies in other regions may affect the relationship. E.g. Yun, Lee, and Ha (2014) proposed that a strengthened zonal gradient of SST between the Indian Ocean, western Pacific, and eastern Pacific may be a possible cause of an enhanced contrast in convective precipitation between South Asia and East Asia. Lee et al. (2017) suggested an enhanced influence of tropical Atlantic SSTs on Korean summer rainfall variations since the mid-1970s.

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Apparent long-term changes in the correlation are present in Figure 3(a). For example, the correlation coefficient between Indian and southern Japan summer rainfall varies from +0.4 to −0.4; and the correlation coefficient between North China and southern Japan summer rainfall varies from +0.4 to −0.8. The long-term change in the Indian–North China rainfall correlation is less obvious in the sliding correlation. The grid-point correlation in the two periods (model years 2040–2060 and 2012–2032) displays a clearer difference in North China (Figure 3(b) and (c)). The region of positive correlation in North China with Indian rainfall tends to be located more northwest in the model compared to observations (e.g. Wu 2017).

The difference in the rainfall relationship between the two periods is explained well by the circulation difference in the model. During model years 2040–2060, an obvious wave pattern is present across continental midlatitude Asia, with an anomalous high over central and East Asia (Figure 3(d)), which is similar to observed (Wu 2002). The anomalous high over East Asia induces southerly winds over North China and northerly winds over Japan, leading

and Jiao (2017). This implies that long-term changes in the Indian–East Asian summer rainfall relationship may occur in the absence of ENSO impacts. In other words, long-term changes in the relationship may be induced by internal atmospheric variability.

### 3.2. Internal variability

The possibility of contribution from internal atmospheric variability to long-term changes in the Indian–East Asian summer rainfall relationship is demonstrated by a 100-years simulation of an AGCM forced by climatological monthly mean SST and sea ice (derived from AMIP). The AGCM used is ECHAM5 (Roeckner et al. 2003), and we use a version with a triangular truncation at zonal wavenumber 63 (T63; equivalent to a horizontal resolution of 1.9°) and 19 sigma levels in the vertical direction. Figure 3(a) displays the correlation of the 21-years running window for the three pairs of JJAS rainfall time series. The domains for calculating the area-mean rainfall in the model are the same as in observations.
China summer rainfall relationship tends to be stronger when a larger Indian rainfall anomaly occurs during a higher mean rainfall period. Lin, Lu, and Wu (2017) performed experiments using a barotropic vorticity equation model with the same anomalous heating over India but different mean winds prescribed over the midlatitudes. They found a notable difference in the midlatitude zonal wave pattern and in the location of the accompanying anomalous anticyclone over East Asia.

We conducted experiments with the barotropic model used by Lin, Lu, and Wu (2017). Anomalous heating was imposed over India and the prescribed mean winds were the average 200-hPa winds during the two periods (2040–2060 and 2012–2032) of the AGCM simulation. When the center of anomalous heating moves from 20°N to 25°N along 72.5°E, an obvious eastward shift in the wave-type response appears, regardless of whether the prescribed mean winds are based on the model years 2040–2060 or 2012–2032 (figures not shown). This indicates that the atmospheric response is sensitive to the location of anomalous heating, which is consistent with Wu (2002) and Wu to above-normal and below-normal rainfall, respectively, in the two regions (Figure 3(b)). During model years 2012–2032, the wave pattern is weak and shifts eastward (Figure 3(e)). The anomalous high over East Asia shifts to Japan. Anomalous lower-level high pressure is situated southeast of Japan (not shown) and anomalous southwesterly winds along the west flank of the anomalous high transport more moisture from lower latitudes, contributing to above-normal rainfall over Japan (Figure 3(e)). As there are no year-to-year changes in the SST forcing, the long-term change in the above relationship in the AGCM simulation is attributable to the impacts of internal atmospheric variability.

3.3. Mean state changes

The atmospheric circulation patterns connecting the variations of Indian and East Asian summer rainfall depend upon the forcing and mean circulation. Thus, it is possible that changes in anomalous forcing and mean winds may lead to fluctuations in the Indian–East Asian rainfall connection. Wu and Jiao (2017) showed that the Indian–North China summer rainfall relationship tends to be stronger when a larger Indian rainfall anomaly occurs during a higher mean rainfall period. Lin, Lu, and Wu (2017) performed experiments using a barotropic vorticity equation model with the same anomalous heating over India but different mean winds prescribed over the midlatitudes. They found a notable difference in the midlatitude zonal wave pattern and in the location of the accompanying anomalous anticyclone over East Asia.

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and Wang (2002). The response, however, does not show a large difference between the two prescribed mean winds (figures not shown).

3.4. Stochastic processes

Interdecadal changes in the relationship may occur due to stochastic processes (e.g. Gershunov, Schneider, and Barnett 2001) or sampling variability (e.g. Cash et al. 2017). To examine the impact of stochastic processes on the relationship, we carried out Monte Carlo test, as in Wu (2016) and Wu and Jiao (2017). Taking the Indian–North China rainfall relationship as an example, the procedure for the Monte Carlo test was as follows. First, two values were randomly selected from the Indian and North China summer rainfall time series for the period 1900–2010 (one from each time series). This was repeated 21 times to obtain two sub-time series with a length of 21 years. Then, we calculated the correlation coefficient between the two 21-years time series. The above processes were repeated 5000 times to obtain 5000 correlation coefficients. After that, we calculated the probability distribution of the correlation coefficient based on the 5000 values obtained above. The distribution was then compared to the maximum and minimum 21-years sliding correlation coefficients in the observations to determine the probability for the observed correlation to occur randomly. A similar procedure was applied to the Indian and southern Japan summer rainfall time series and the North China and southern Japan summer rainfall time series. The results are shown in Figure 4. Wu and Jiao (2017) performed similar Monte Carlo test for the Indian–North China rainfall relationship.

For the Indian–North China rainfall correlation, the maximum and minimum correlation coefficients in the observations are 0.80 and 0.01, respectively, which are around the 99% and 5% level of the Monte Carlo correlation distribution, respectively (Figure 4(a)). For the Indian–southern Japan rainfall correlation, the observed maximum and minimum correlation coefficient is close to the 95% and 2% level, respectively (Figure 4(b)). For the North China–southern Japan rainfall correlation, the maximum correlation coefficient in observations is below the 95% level (Figure 4(c)). These results indicate that the possibility that the observed change in the Indian–North China summer rainfall correlation being due to stochastic processes cannot be excluded.

4. Concluding remarks

The relationship between summer rainfall variations over India and East Asia displays long-term changes in both observations and climate model simulations, and there are different perspectives on what may have contributed to these long-term changes. ENSO’s impact may be a factor, but it cannot totally explain the observed long-term change in the Indian–North China summer rainfall relationship. Both a climatological SST–forced AGCM simulation and CMIP5 coupled model simulations indicate an important role played by internal atmospheric variability in the change of the Indian–North China summer rainfall relationship; plus, Monte Carlo test indicates that the role of random processes in the observed long-term changes of the Indian–East Asian summer rainfall relationship cannot be totally excluded.

It is possible that different factors may play their respective roles in interdecadal changes in the above relationship at different times. Further analysis of observations and numerical model simulations are needed to advance our understanding of the contributions of different factors in the long-term changes in the relationship between Indian and East Asian summer rainfall.
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