Reduction of mid-summer rainfall in northern India after the late-1990s induced by the decadal change of the Silk Road pattern

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Abstract
Variation of summer rainfall can pose substantial challenges to water resources and agriculture in northern India, which includes the most fertile land in India, i.e. the Ganges Plain. This study identifies a significant rainfall reduction in northern India during its peak rainy season (July and August) after the late-1990s, based on observational and reanalysis data since 1958. This rainfall reduction is about 0.86 mm d\(^{-1}\), equivalent to 8.3% of the climatological mean. We suggest that the decadal reduction of northern Indian rainfall is induced by the decadal change of the Silk Road pattern (SRP), which is an atmospheric teleconnection pattern along the upper-tropospheric Asian westerly jet. After the late-1990s, corresponding with the decadal phase shift of the SRP, there is a cyclonic anomaly over West Asia, which can reduce rainfall in northern India. Furthermore, this rainfall reduction is unprecedented since the beginning of the 20th century, when observational data are available. Possible roles of the lower-tropospheric circulation changes and the Atlantic Multidecadal Oscillation are discussed.

1. Introduction

Summer rainfall accounts for up to 80% of the annual precipitation in India (Turner and Annamalai 2012). In India, as an agrarian-based economy and with 60% of the population being employed in agriculture (Amrith 2016), the lives and livelihoods are sensitive to the fluctuation in rainfall, particularly during the rainy season, i.e. summer. For example, the Indian economy is estimated to have suffered a loss of billions of dollars due to the 19% reduction of rainfall in summer 2002 (Gadgil et al 2004). Thus, it is of great socioeconomic importance to understand the variations of Indian summer rainfall.

In particular, the northern part of the Indian subcontinent is densely populated and includes the most fertile land in India, i.e. the Ganges Plain. The plain is the world’s most intensely farmed area, with more than 70% of the plain being used for agriculture, and provides about half of the total food production in India (Pal et al 2009). Therefore, a decrease in crop production in northern India, driven mainly by droughts (Lesk et al 2016, Nath et al 2017), could affect the food security of the country. However, the precipitation in northern India has been less documented relative to the all-Indian summer rainfall, which is well known to be influenced by Atlantic Multidecadal Oscillation (AMO; Goswami et al 2006, Lu et al 2006, Li et al 2008, Luo et al 2011, Joshi and Ha 2019), Pacific Decadal Oscillation (Krishnan and Sugi 2003, Krishnamurthy and Krishnamurthy 2014), El-Niño Southern Oscillation (Rasmusson and Carpenter 1983, Krishnamurthy and Goswami 2000, Ashok et al 2019), Indian Ocean dipole (Ashok et al 2001, Gadgil et al 2004, Ummenhofer et al 2011), and Eurasian snow cover (Liu and Yanai 2002, Zhao and Moore 2004).
Extratropical circulations, in addition to tropical monsoonal flows, can significantly affect the summer rainfall in India, particularly in northern India. It has been documented that the upper-tropospheric cyclonic/anticyclonic circulation anomaly over West Asia can suppress/enhance rainfall in northern India (Ramswamy 1962, Krishnan and Sugi 2001, Krishnan et al 2009, Saeed et al 2010, Yadav 2017, Chowdary et al 2021). The cyclonic anomaly over West Asia corresponds to a southward displacement of the Asian jet. Recently, Chowdary et al (2021) identified in both the observation and a model that the southward displacement of the Asian jet reduces the summer precipitation over central and northern India, and suggested that this jet displacement induces the lower-tropospheric anticyclonic anomaly and resultant reduced rainfall. This cyclonic/anticyclonic anomaly over West Asia is a component of the Silk Road pattern (SRP), i.e. a teleconnection pattern that propagates along the upper-tropospheric Asian westerly jet (Lu et al 2002, Enomoto et al 2003, Ding and Wang 2005, 2007, Saeed et al 2010, Yadav 2017, Hong et al 2021). The SRP, which is excited in the North Atlantic and propagates southeastward, can affect the Indian rainfall, which in turn, may favor the downstream components of SRP over East Asia and the North Pacific (e.g. Ding and Wang 2005). The SRP exhibits a clear decadal change after the late-1990s (Hong et al 2017, Wang et al 2017), and this change is suggested to be responsible for regional climate variations over the Eurasian continent (Shi et al 2019, Du et al 2020).

Therefore, we speculate that summer rainfall in northern India might experience a decadal change after the late-1990s influenced by the decadal change of SRP. We focus on the mid-summer, which is the peak rainy season in northern India and is also the period of significant decadal change of SRP (Hong et al 2018). Testing this hypothesis is the main motivation of the present study.

2. Datasets

The circulation data used in this study include the Japanese 55 year Reanalysis dataset with a horizontal resolution of 1.25° × 1.25° (JRA55; Kobayashi et al 2015), the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis dataset with a horizontal resolution of 2.5° × 2.5° (NCEP1; Kalnay et al 1996), the NCEP-Department of Energy reanalysis dataset with a horizontal resolution of 2.5° × 2.5° (NCEP2; Kanamitsu et al 2002), the fifth generation of European Centre for Medium-Range Weather Forecasts reanalysis dataset with a horizontal resolution of 2.5° × 2.5° (ERA5; Hersbach et al 2020), the 20th century reanalysis version 3 dataset with a resolution of 1° × 1° (20CR; Compo et al 2011). The JRA55 and NCEP1 datasets are from 1958 to 2018, the NCEP2 and ERA5 datasets are from 1979 to 2018, and the 20CR dataset is from 1901 to 2015. The results obtained by the JRA55 are shown in the text, and those obtained by other reanalysis data are shown in the supplementary figures (available online at stacks.iop.org/ERL/16/104051/mmedia). The precipitation data applied in this study is from the India Meteorological Department, with a time span of 1901–2018 and a horizontal resolution of 0.25° × 0.25° (Pai et al 2014).

In this study, we focus on July–August (JA), during which the northern India experiences the heaviest rainfall and the SRP shows a clearer decadal variation. The SRP is defined as the first empirical orthogonal function (EOF) mode of the JA-mean 200 hPa meridional wind within the domain (20°–60°N, 0°–150°E), and the corresponding standardized principal component is referred to as SRP index (SRPI), following previous studies (Yasui and Watanabe 2010; and many others). A nine year Gaussian low-pass filter is used to obtain the decadal component of a variable. Considering autocorrelations, the statistical significance is determined according to the effective degrees of freedom ($N_{\text{dof}}$), which is calculated by:

$$N_{\text{dof}} = N(1 - r_1r_2)/(1 + r_1r_2)$$

where $N$ is the size of the sample and $r_1$ and $r_2$ are the lag-1 autocorrelations of the two time series, respectively (Bretherton et al 1999).

3. Results

The 200 hPa horizontal wind anomalies regressed onto the SRPI are characterized by a clear wave pattern over North Atlantic and the Eurasian continent (figure 1(a)). The wave starts from the high latitudes over North Atlantic, propagates southeastward into the Asian westerly jet, and then propagates eastward along the jet. In particular, there is an anticyclonic anomaly over West Asia, or to the northwest of the Indian subcontinent. In addition, the SRPI presents an evident decadal change since 1973: from the positive phase during 1973–1998 to the negative phase during 1999–2018 (figure 1(b)). Before 1973, the decadal variation of SRP is much weaker. Actually, analyses using the 20CR dataset from 1901 also indicates that in the extended period, the decadal variation of SRP has been strengthened since the mid-1970s (figure S6(e)) which has also been pointed out in previous studies (Wang et al 2017, Stephan et al 2019). Accordingly, we use these two periods, i.e. 1973–1998 and 1999–2018, to represent the decadal change of the SRP. The decadal variation of the SRPI explains 36% of the total variance during the period of 1973–2018, confirming that the SRP does have a clear variation on the decadal timescale. Very similar results are obtained from other reanalysis data (figure S1).
Figure 1. (a) The July–August (JA)-mean 200 hPa horizontal wind anomalies (vectors, units: m s$^{-1}$) regressed onto the standardized Silk Road pattern index (SRPI). Shading denotes the meridional wind anomalies. The black box delineates the region (20$^\circ$–60$^\circ$ N, 0$^\circ$–150$^\circ$ E) used to define the SRPI. Only anomalies statistically significant at the 0.05 level based on the Student's t test are plotted. (b) Time series of the original (bars) and decadal (black line) components of the standardized SRPI.

Figure 2 (a) shows the difference in rainfall between the two periods. There are significant negative anomalies over the majority region of northern India. We define a northern Indian rainfall index (NIRI) as the precipitation anomalies averaged within the domain (20$^\circ$–30$^\circ$ N, 75$^\circ$–95$^\circ$ E) to quantitatively estimate the decadal variation of rainfall. The decadal component of NIRI turns from a positive phase to a negative phase in the late 1990s (figure 2(b)), and explains 29% of the total variance during the period of 1973–2018. Note that figure 2(b) starts from 1973, rather than 1958 in figure 1(b), to highlight the dominant period of decadal variation. The correlation coefficient between the decadal components of NIRI and SRPI is 0.81, significant at the 95% level considering the effective degrees of freedom. The shift point is 1999, same as that for the SRPI. The rainfall in northern India was mostly above normal during the former period (19 out of 26 years) and below normal during the latter period (17 out of 20 years), emphasizing the role of the decadal component in dominating the rainfall variation. The rainfall reduction averaged within this area is 0.86 mm d$^{-1}$, statistically significant at the 99% confidence level, and is equivalent to 8.3% of the climatological mean (10.45 mm d$^{-1}$).

We quantify the upper-tropospheric cyclonic/anticyclonic circulation anomaly over West Asia, which directly affects the northern Indian rainfall, by defining a West Asia anticyclonic index (WAACI) as the vorticity anomalies averaged within the domain (35$^\circ$–45$^\circ$ N, 50$^\circ$–75$^\circ$ E) (figure 3(a)). This index is multiplied by minus one so that positive values indicate anticyclonic anomaly that enhances the northern Indian rainfall (Krishnan and Sugi 2001, Krishnan et al 2009, Saeed et al 2010, Yadav 2017). As mentioned previously, this anticyclonic anomaly is a component of the SRP, and this can be confirmed by the high correlation coefficients between WAACI and SRPI, which is 0.90, 0.96 and 0.86 for the original time series, interannual and decadal components, respectively. The shift point for WAACI is identified to be 1998, in good agreement with the NIRI and SRPI (1999). The decadal component of WAACI explains 32% of the total variance during the period of 1973–2018, similar to the ratios for the NIRI and SRPI (36% and 29%).

The purpose of defining WAACI is that as a component of SRP, the anticyclonic anomaly over West Asia can directly affect rainfall in northern India. In addition, WAACI can be used to depict conveniently daily and subseasonal variations, while the EOF-based SRPI cannot.

Figure 4 shows the variations of NIRI and WAACI, with the x-axis showing years and y-axis showing days in summer. We applied an 11-point running mean to NIRI and WAACI for both the x and y directions to filter out the interannual and synoptic components. From July to August, both the NIRI and WAACI are generally positive before the late-1990s and turn to be negative afterwards, despite some fluctuations, particularly for the NIRI. During June, the NIRI tends to be positive before 2005 and negative afterwards, but this change does not match with the WAACI (see also figure S4(a)). On the other hand,
Figure 2. (a) Difference of the JA-mean precipitation between 1999–2018 and 1973–1998 (units: mm d$^{-1}$). The black box indicates the northern Indian region (20$^\circ$–30$^\circ$N, 75$^\circ$–95$^\circ$E) used to define the northern India rainfall index (NIRI). Marked areas indicate anomalies statistically significant at the 0.05 level. (b) Time series of the original (bars) and decadal (solid line) components of the NIRI (units: mm d$^{-1}$). The decadal component of SRPI (dashed line) is also shown to facilitate comparison.

4. Discussion

We also examined the lower-tropospheric wind anomalies in association with the decadal variations of northern Indian rainfall and SRP. Figure S7(a) shows the 850 hPa wind difference between 1999–2018 and 1973–1998 using the JRA55 reanalysis data. There are some significant wind anomalies in Indian
Ocean and the Bay of Bengal. Among these circulation anomalies, the northerly anomalies extending from the Bay of Bengal to northern India might play a role in the northern Indian rainfall reduction. However, they are absent in all the other reanalysis datasets (figures S7(b)–(d)). Therefore, we conclude that the huge discrepancies between the current reanalysis datasets prevent us from well understanding the possible role of lower-tropospheric circulations in affecting the rainfall reduction in northern India.

Previous studies suggested that the AMO can modulate the decadal variation of the SRP (Hong et al 2017, Wang et al 2017, Sun et al 2019). When AMO is in a warm phase, the SRP tends to present a cyclonic circulation anomaly over West Asia, implying that rainfall would decrease in northern India according to the present results. However, the correlation coefficient between the AMO index and NIRI is only $-0.063$ during 1901–2015, much lower than that between the SRPI and NIRI (0.40) or that between NIRI and WAACI.
the WAACI and NIRI (0.48). Here the AMO index is calculated by averaging the annual mean sea surface temperature anomalies over the North Atlantic Ocean (0°–60°N, 75°–7.5°W) with linear trend removed, following Enfield et al (2001), and all the indexes are for the decadal components. These results suggest that the JA northern Indian rainfall is more closely related to the decadal variation of SRP than to the AMO, and imply that the decadal variation of SRP might be influenced by other factors besides the AMO.

Various previous studies showed that the Indian summer precipitation experienced a decreasing trend since the early 1950s (e.g. Naidu et al 2015, Roxy et al 2015, Agrawal et al 2019, Kumar et al 2020, Seetha et al 2020, Ayantika et al 2021), while some studies suggested the revival of summer monsoon precipitation in northern India in the recent two decades (Jin and Wang 2017, Huang et al 2020). These changes in precipitation have been attributed to the monsoonal circulations, land–ocean temperature gradient, global warming, anthropogenic aerosol emissions, and land use and land cover. All these studies focused on the entire monsoon season, i.e. JJAS, which, in addition to the differences in concerned regions and datasets, makes it difficult for direct comparisons with the present study. Though Patil et al (2019) dealt with the peak summer monsoon months of July–August, they focused on the influences of sea surface temperature and anthropogenic aerosol, obscuring the temporal variation of precipitation. This study indicates that the rainfall decreases after the late-1990s in northern India, and the decrease occurs mainly during the peak rainy season (July–August), and suggested that the decadal change of upper-tropospheric circulation, i.e. the SRP, attributes to the rainfall reduction.

Finally, although the SRPI and NIRI show similar decadal variations since 1973, they exhibit distinct variations before 1973. For instance, the most remarkable positive phase of NIRI appears over 1925–1945, which apparently cannot be explained by the SRP, if assuming the reliability of 20CR data is high.

**Figure 5.** (a) Same as figure 2(a), but for 1999–2018 minus 1901–1998. (b) Same as figure 2(b), but for an extended period of 1901–2018.
The decadal variation of JA rainfall in northern India may be attributed to some other factors before 1973.

5. Conclusions

In this study, we identify that the rainfall decreases significantly after the late-1990s in northern India, including the Ganges Plain, during the peak rainy season (July and August). This rainfall reduction from the former period (1973–1998) to the latter period (1999–2018) is equivalent to 8.3% of the climatological mean, and can be explained by the decadal change in the SRP, i.e. shifting from the positive phase in the former period to the negative phase in the latter period. This decadal shift of SRP corresponds to the cyclonic anomaly over West Asia, which induces the rainfall decrease in northern India. This rainfall reduction in northern India is found to be unprecedented, at least from the beginning of the 20th century when the instrumental data are available.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://rda.ucar.edu/datasets/ds628.1/.

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