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Western Shifting of Extreme Rainfall Events over the different Indian River Basins in the last 119 years

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Introduction

- Climate extremes such as droughts and intense rainfall events are expected to strongly influence the global/regional water resources in addition to the growing demands for freshwater.

- **Hydro-climatic extremes** can have severe impacts on different socio-economic sectors, such as agriculture, water resources, health, ecosystem services, urban infrastructure, etc.

- In the wake of recent global warming, an increase in extreme weather events such as extreme rainfall is observed globally, which has a severe impact on natural and man-made ecosystems (IPCC, 2014; Libertino et al., 2019; Papalexiou & Montanari, 2019).

- India's large population depends on the summer monsoon rainfall for agriculture (Turner & Annamalai, 2012), which is affected by extreme rainfall over the IRBs (Devanand et al., 2019). Floods due to extreme rainfall alone amounted to 10% of global economic losses (Roxy et al., 2017).

- In recent decades, it was observed that around 20 to 80 million of the global population is affected by floods every year, whereas India has observed the most significant loss to life and property due to extreme rainfall events (EM-DAT, 2019).

- According to Mall et al. (2006), to intensify in-depth research work required on recent experiences in climate variability and extreme events, and their impacts on regional water resources.

Need of Research

How the hydro-climate extremes such as extremes rainfall, changes over the different Indian River Basins (IRBs)?

Objectives

- Analyze the rainfall distribution over the different Indian River Basins (IRBs)

- Changes in rainfall extremes in a 40-year time interval, and

- Spatially shifting patterns of the extreme rainfall events over the IRBs during 1901-2019.

Methodology

The intensity of the extreme rainfall events is computed based on the grid-wise rainfall distribution and categorized as per India Meteorological Department (IMD) criteria (http://www.imdpune.gov.in/Weather/Reports/glossary.pdf). According to that, the intensity of rainfall events between 64.5 and 124.4 mm / day is considered as heavy rainfall (HR), the rainfall events between 124.5 and 244.4 mm /day is considered as very heavy rainfall (VHR), and the rainfall events are greater than and equal to 244.5 mm /day is considered as extremely heavy rainfall (EHR).

Generalized Extreme Value (GEV) Distribution

The GEV distribution is used to estimate the return level of rainfall events at every grid point in the study. The GEV distribution is based on the block maxima theory and is used to compute the annual maxima of daily gridded rainfall to estimate the fitted GEV parameters; location (μ), scale (Ψ), and shape (ξ) parameters (Bhatia & Ganguly, 2019; Ghosh et al., 2012; Mannshardt-Shamseld in et al., 2012). Let's suppose Rm is the annual maximum of daily rainfall in the used rainfall series, then GEV distribution is defined as ;

$$P_r\,(R_m \leq R) = \exp\left[-\{1+\xi(R-\mu)/\Psi\}^{-1/\xi}\right] \quad \text{.................... (1)}$$

$$1/n = \left[1+\xi\,(R_n-\mu)\,/\Psi\right]^{1/\xi} \quad \text{.................... (2)}$$

$$R_n = \begin{cases} \mu + \Psi n^{\xi} - \dfrac{1}{\xi}, & if \;\; \xi \neq 0 \\ \mu + \Psi \;\log n \;, & if \;\; \xi = 0 \end{cases} \quad \text{.................... (3)}$$

Percentage Departure

The study computes the grid-based percentage departure of realized rainfall from average rainfall. The percentage departure of rainfall for an individual year at every grid point was expressed as:

$$\%\ \text{Departure} = \left(\frac{\text{Annual rainfall for an individual year} - \text{Average of longterm annual rainfall}}{\text{Average of longterm annual rainfall}}\right) 100$$

.... (4)

Extreme Indices

The ETCCDI climate indices are calculated using CDO to describe the extreme rainfall changes in the IRBs. The ETCCDI indices are used to estimate the spatial extent of rainfall extremes considering their significance toward frequency and intensity. The ETCCDI indices categorize the rainfall extremes from moderate to extreme events that occur multiple times per year and once per year, respectively (Herold et al., 2017).

Standardized Precipitation Index

Standardized Precipitation Index (SPI) is a probability (i.e., statistical) index representing abnormal wetness and dryness. The decadal changes in SPI at 12- months running window is used to compare the dry to wet condition across IRBs.

MK-Trend Test

The trend analysis performed at every grid point is carried out using the Mann–Kendall trend test method to consider linear trends. Sen's method is used to estimate the slope of the trend.

Results & Discussion

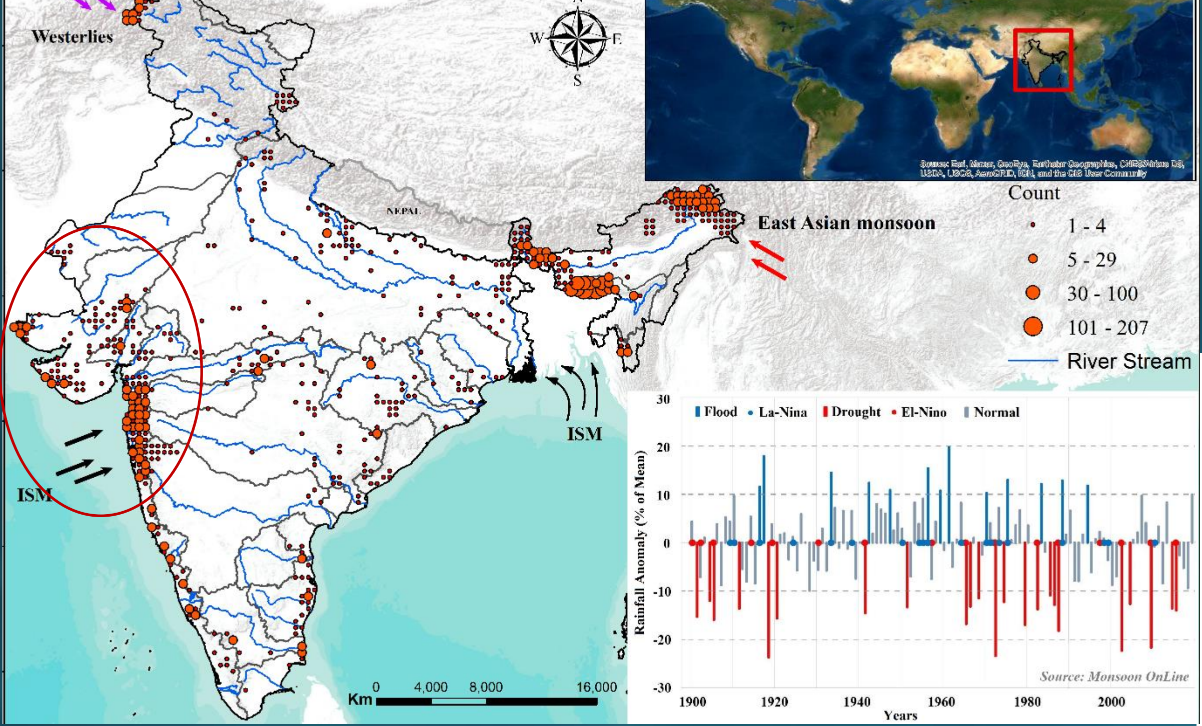


Figure 1. Overview of the Indian River Basins (IRBs).

West flowing and western part of the Indian river basins (IRBs) shows the high number of rainfall extremes at 99.99th percentile with having threshold values about ≥300 mm/day in the period of time from 1901 to 2019.

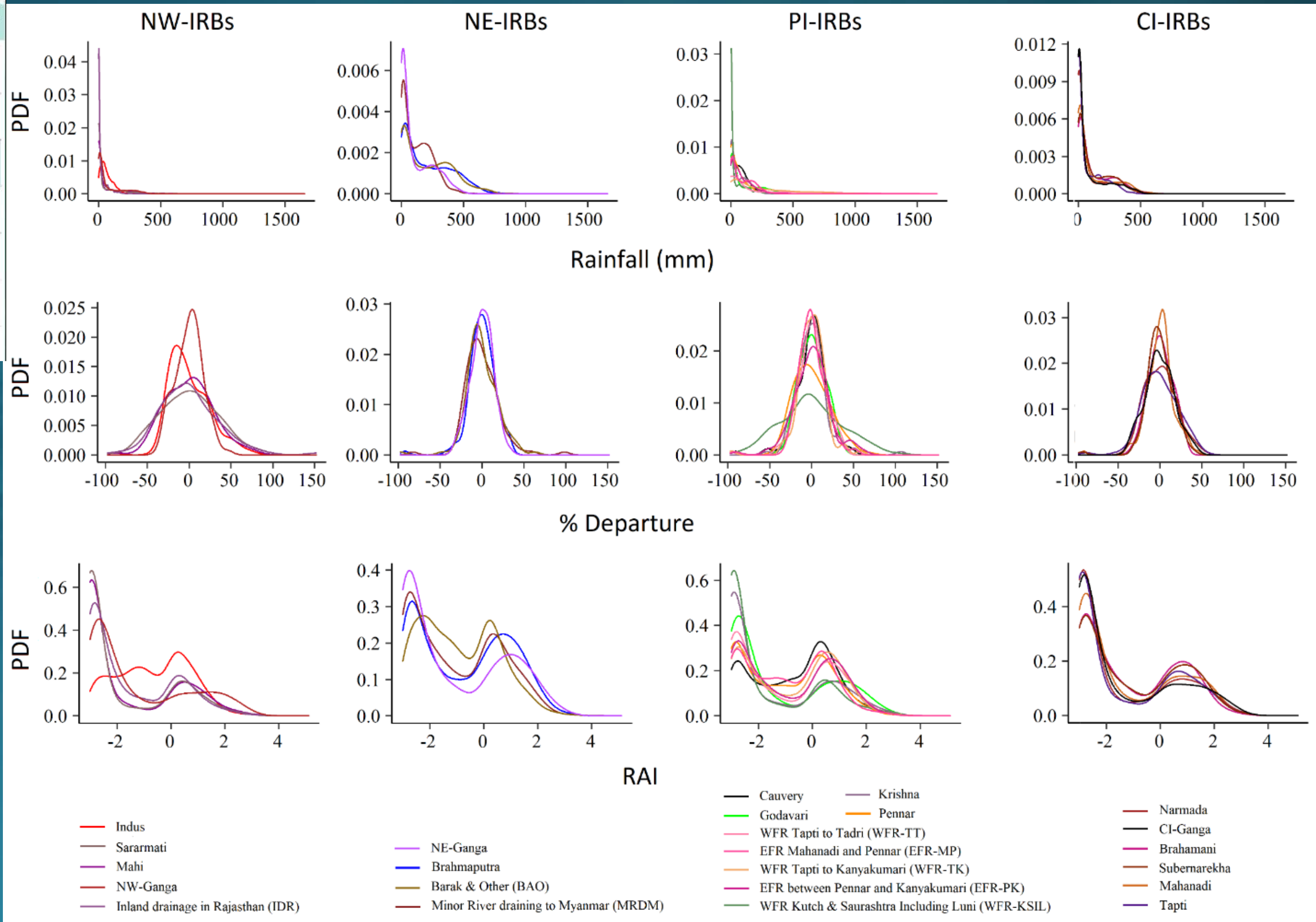


Figure 2. Probability distribution of monthly sum rainfall, percentage departure, and the rainfall anomaly over the North-West India river basins, North-East India river basins, Peninsular India river basin, and Central-Indian River Basins.

Rainfall Distribution Over the IRBs

The excess monthly rainfall departure (>20%) has been observed over the Brahmaputra and NE-Ganga river basins. While Brahmaputra of NE-IRBs has been observed the highest probability of rainfall anomaly (0 ≤ RAI ≥ 2).

The high probability of monthly sum rainfall (300–1000 mm) has been observed in WFR-TT and WFR-TK in PI-IRBs. Meanwhile, in the monthly sum rainfall distribution between 0 and 300 mm, the Narmada river basin shows a high probability among all CI-IRBs.

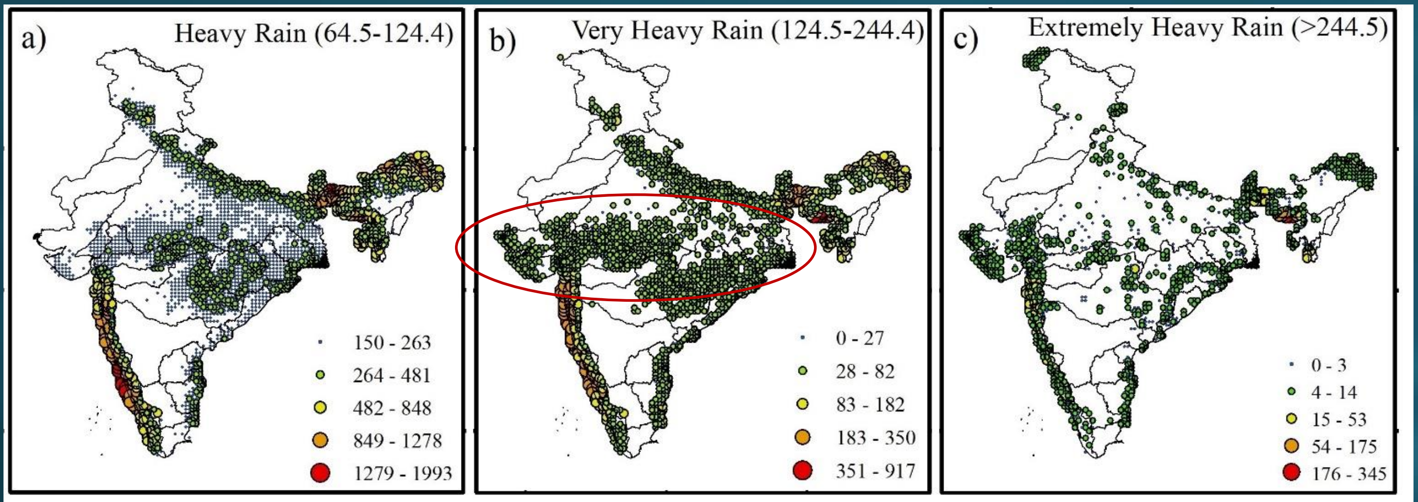


Figure 3. Long-term (1901-2019) observed number of extreme rainfall according to Indian Meteorological Department criteria for the intensity of (a) heavy rainfall (HR), (b) very heavy rainfall (VHR), and (c) extremely heavy rainfall (EHR).

Figures 3 show that the largest number of HR to EHR events are concentrated over the west-flowing river basins of the PI-IRBs, including WFR-TT, WFR-TK, and EFR-PK. The CI-IRBs experienced more HR events instead of EHR events, while IDR, Krishna, and Cauvery showed none of the EHR events.

In the recent decades of the 21st first century, the maximum number of extreme rainfall events were observed over the WFR-TT and BAO and the lower part of the Mahanadi and Godavari basins. However, WFR-KSIL experienced the maximum number of EHR events over the basin last 9-year (2011-2019) (Figure 4).

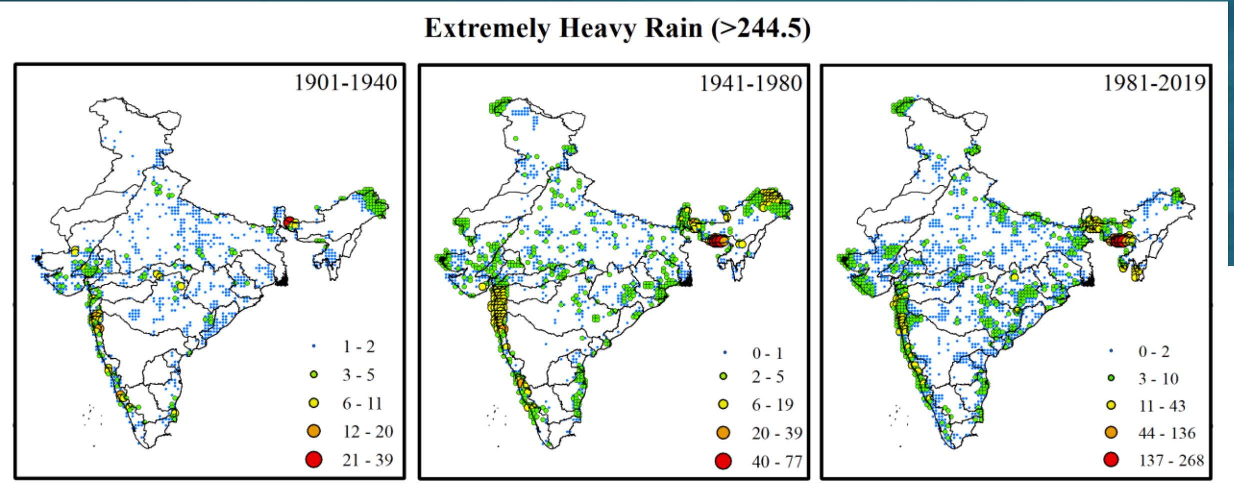


Figure 4. The number of extreme rainfall events for the extremely heavy rainfall (EHR).

During the recent period 1981-2019, EHR events have risen spatially in widespread new grids over the WFR-TT and lower Narmada basin.

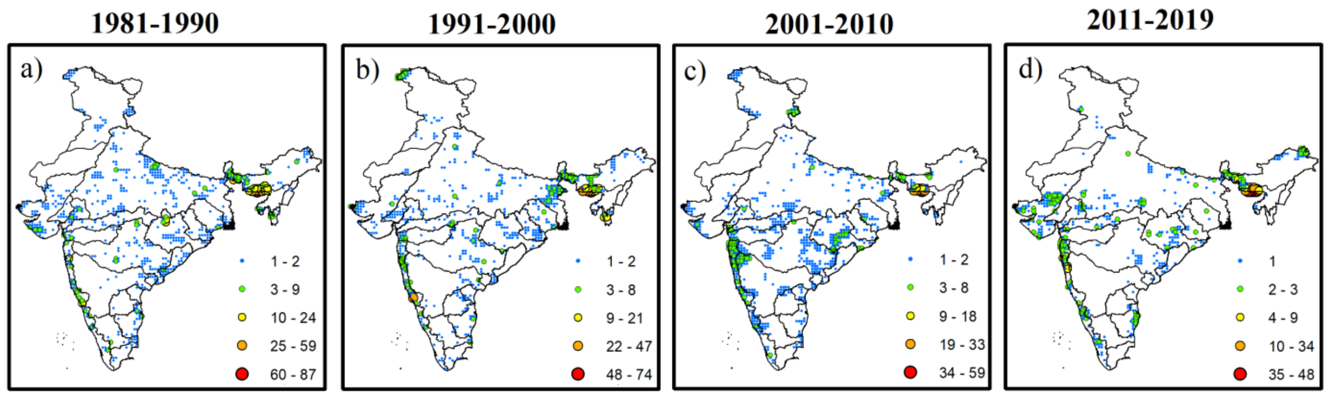


Figure 5. Decadal variation of the number of extreme rainfall events, extreme heavy rainfall (>244.5 mm), for the decadal time period 1981-1990, 1991-2000, 2001-2010, and 2011-2019.

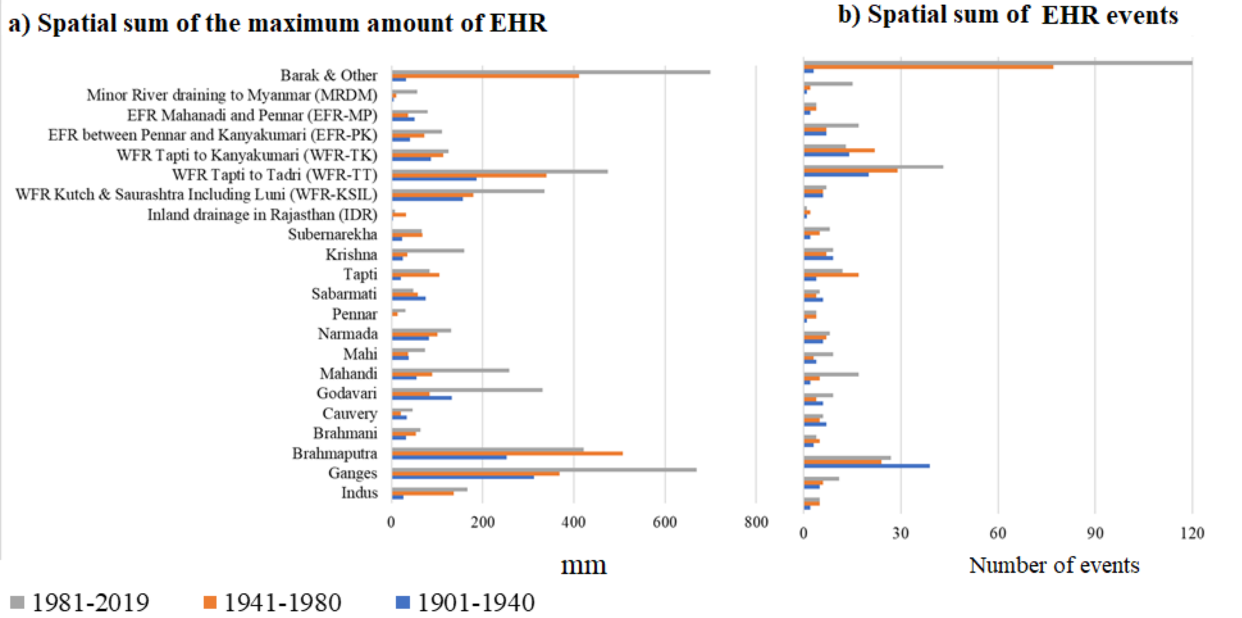


Figure 6. Calculated spatial sum of the maximum amount and number of the EHR (a-b) events over the 22 major IRBs.

The spatial distribution of EHR events over the IRBs shows large variability in the total rainfall maxima. The largest over the Ganga and the smallest over the Cauvery and Pennar river basins have been observed during 1981-2019 (Figure 6).

The 99.50 percentile of the 5-day accumulated rainfall shows a scattered pattern all over the IRBs.

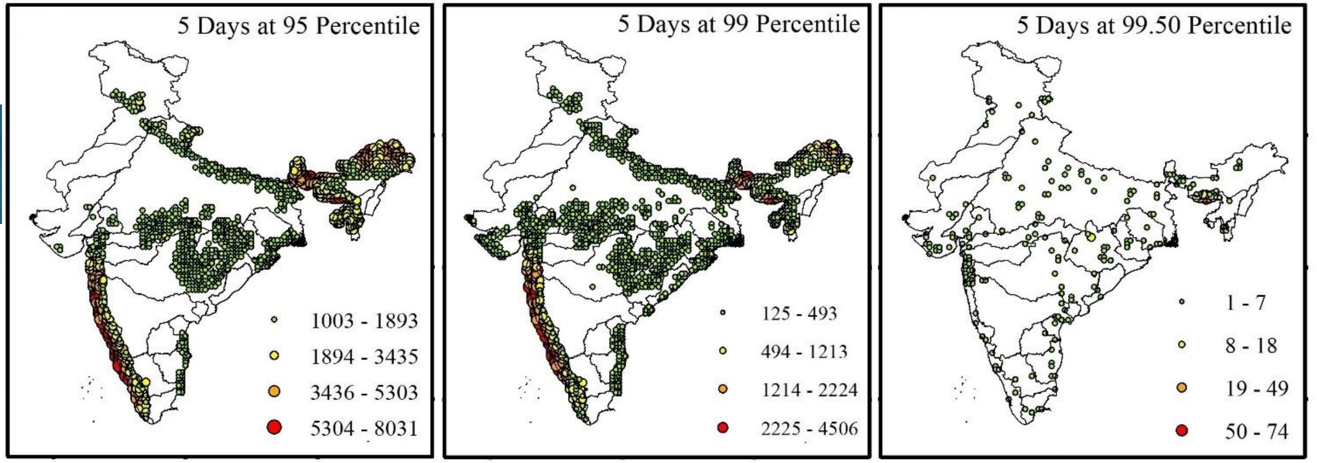
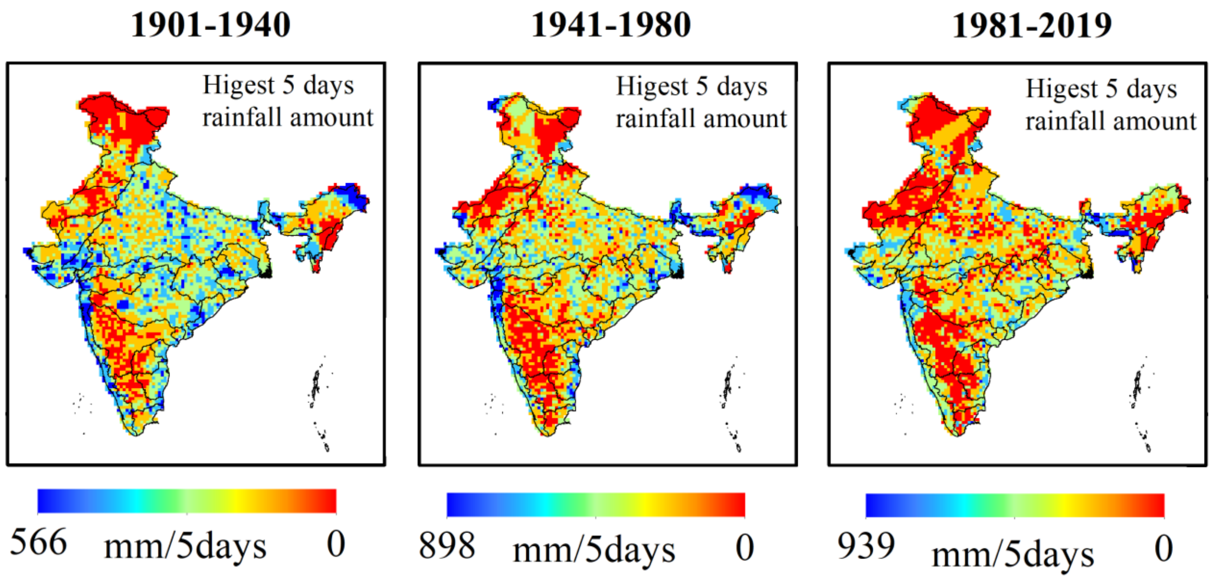


Figure 7. Accumulated 5 days at 95, 99, and 99.50 percentile having threshold greater than and equal 124, 233, and 292 mm/5 days rainfall, respectively.



The figure 8 shows the increasing consecutive 5-day rainfall amount in between 1981-2019.

Figure 8. Spatial variability in the maximum 5-day rainfall estimated by using Expert Team on Climate Change Detection and Indices over the Indian river basins.

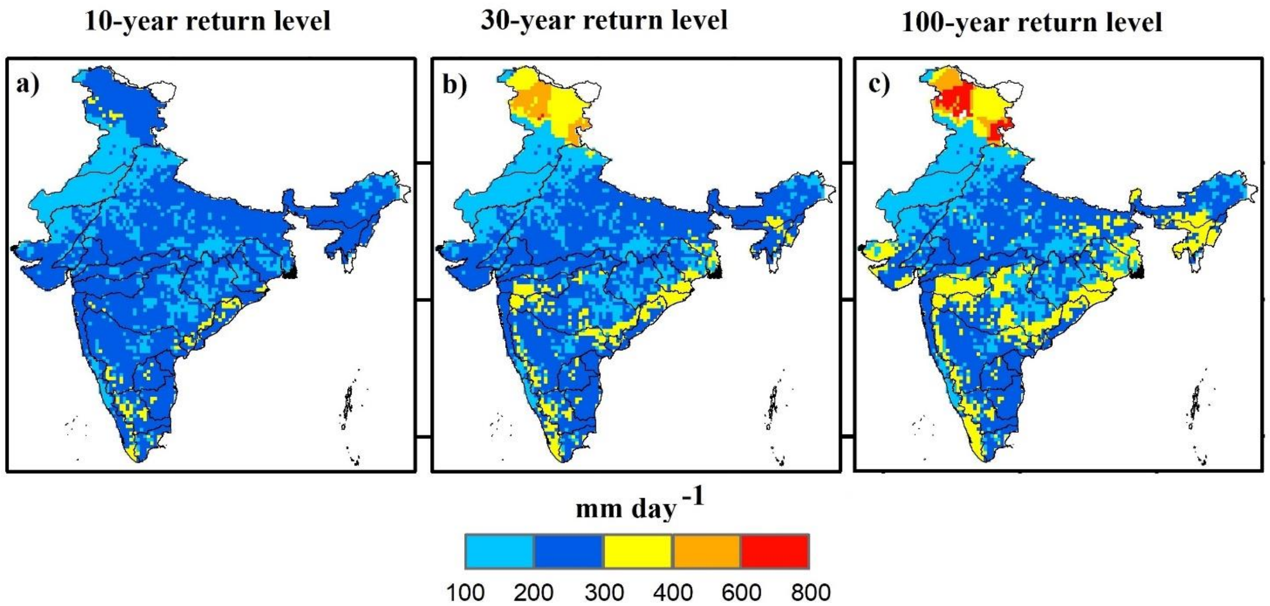


Figure 9. Spatial grid-based estimation of return level of rainfall extremes over the Indian river basins (IRB) at10-year (a), 30-year (b), and 100-year (c) return levels, using 1901–2019 data.

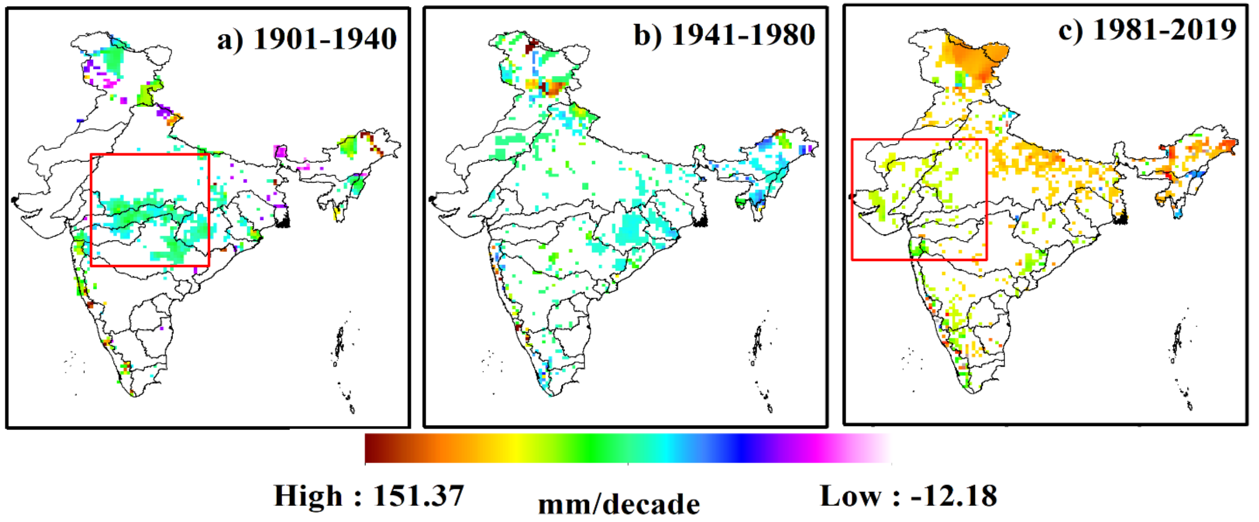


Figure 11. The decadal trend of spatial rainfall distribution at 40 years's time interval (a–c) in the red box shows the positive trend of rainfall over the Indian River Basins (IRBs). Figures show only those values significant at 95% confidence level are shown.

In Figure 9b-c, the Indus, west-flowing river basins of peninsular India, and the meanwhile north east belt of Ganga and NW-IRBs show the expected 3.3% and 1% probability of extreme rainfall events in 30- and 100-year return level

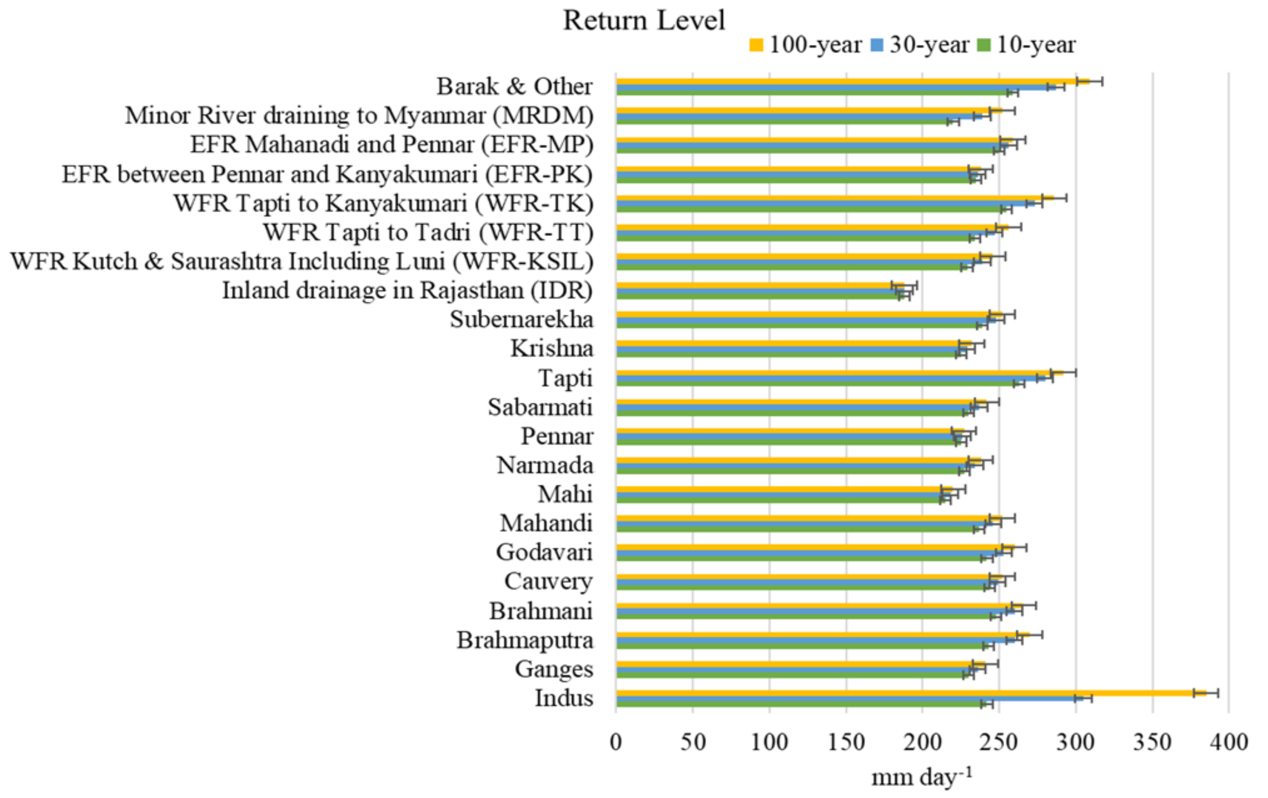


Figure 10. Spatial mean grid-based estimation of return level distribution of rainfall extremes per day over the 22 major IRBs at 10-years (a), 30-year (b), and 100-year (c) return period, using 1901–2019.

A significant increase in the trend of occurrence of rainfall (94 ± 10 mm/decade) has been observed in WFR-KSIL and WFR-TT at 95% at the end of twentieth and beginning of the 21st century (1981-2019),

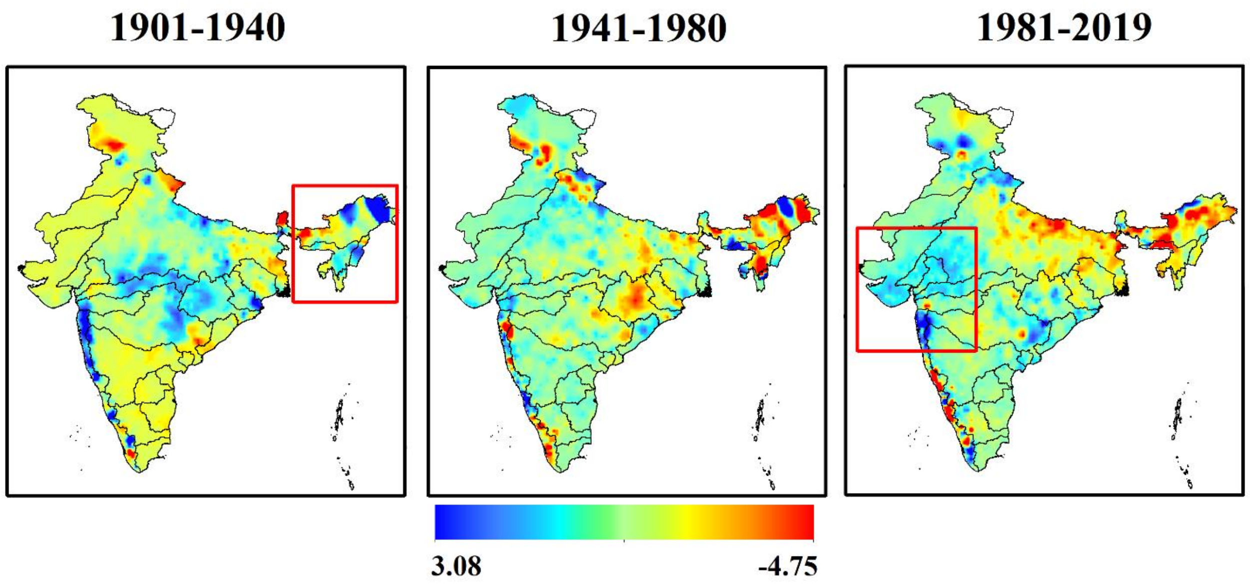


Figure 12. Shifting trend of the JJAS rainfall at 40-year time interval based on the observed rainfall period (1901–2019), the rectangular red box represents the shifting trend of the rainfall.

During the 1901-1940 era, the Cauvery and EFR-PK river basins of the PI-IRBs show slightly to a very wet state (0.5 ≤ SPI ≤ 2), and Brahmani shows the extremely wet state (SPI ≥ 2.5) during the decades 1901-1910 and 1931-1940. In 1941-1980, the decades 1941-1950 and 1971-1980 showed the moderate wet to a very wet condition in the Indus and central part of the Ganga river basin having SPI between 1 ≤ SPI ≥ 2, whereas very to extreme wet condition (1 ≤ SPI ≥ 2) over the WFR-KSIL during decades 1961- 1970.

However, during 1981-2019, drastic changes in SPI (0 ≤ SPI ≥ 3) were observed, indicating a shift in extreme rainfall events toward the central-western part of the IRBs (Figure 13).

The shifting trend of monsoon rainfall toward the NW-IRBs, including WFR-KSIL, Sabarmati, Mahi, and lower part of the Narmada basin (Figure 12).

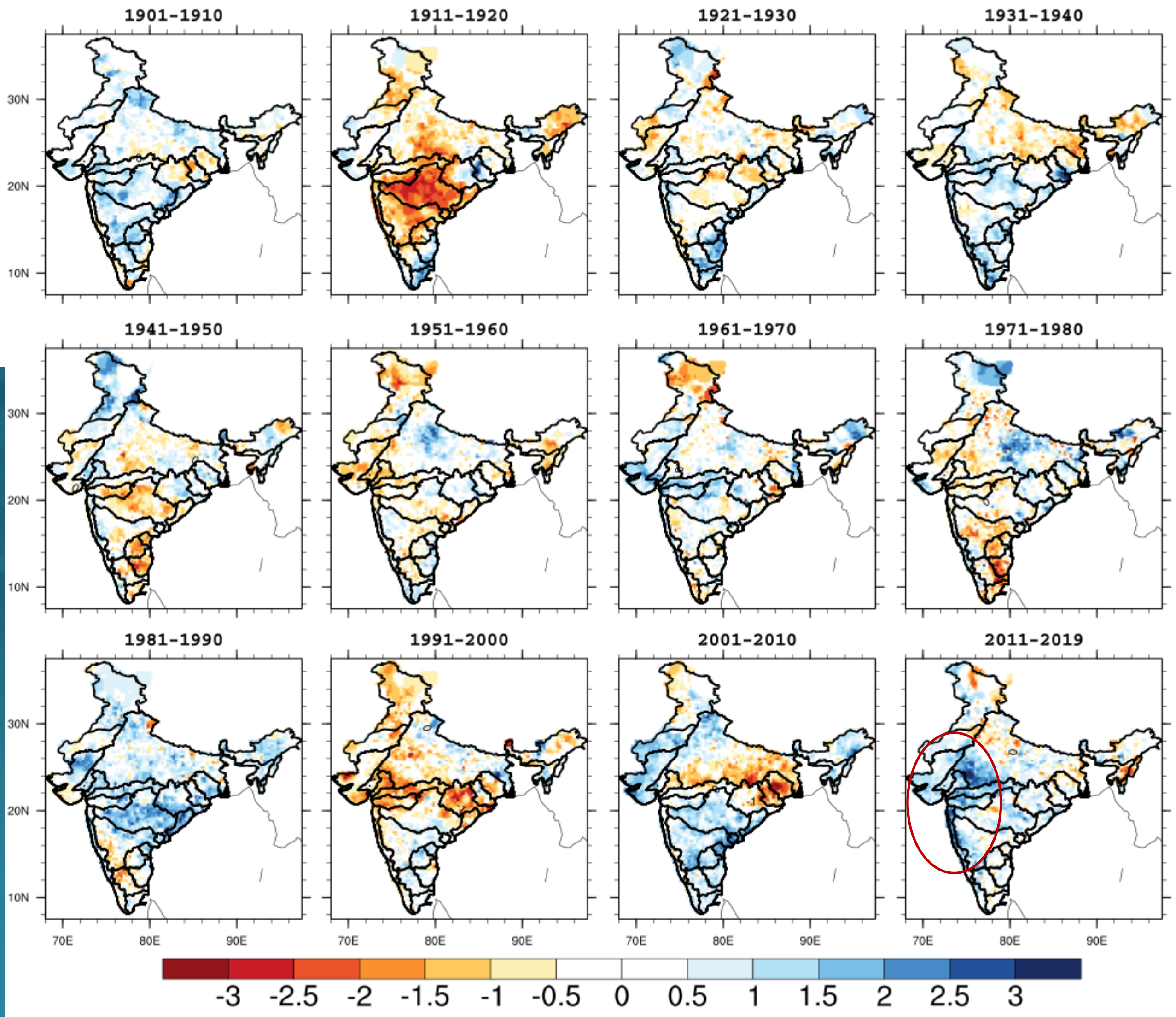


Figure 13. Decadal changes in average intensity of estimated standardized precipitation indices at a monthly time spanning over the Indian river basins.

Conclusion

- The Ganga, west-flowing river basins of the homogeneous region of Peninsular India, and Northeast homogeneous river basins experienced the highest rate of spatial variability of extreme rainfall events in the last 39-year compared to the earlier and mid-21st century.

- Study concluded that the western and central IRBs experienced increasing VHR to EHR events in the last 39 years.

- An increased intensity in observed maximum consecutive 5-day rainfall has been observed in the last two decades of the 21st century.

- The study determined an increase in the extreme events (15% – 58.74%) over the western ghats in west-flowing river basins of IRBs in the last 119 years.

- The findings of the study revealed a shift in extreme rainfall events over the western river basins of the central India homogeneous climate region.

The finding of this research has been published in **Earth And Space Science**, in **American Geophysical Union (AGU)**

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RESEARCH ARTICLE

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Spatio-Temporal Changes in Extreme Rainfall Events Over Different Indian River Basins

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Key Points:

- High-resolution gridded data sets used for the assessment of the rainfall extremes over the Indian River Basins (IRBs)
- A western shift in a significantly increasing trend of extreme rainfall events was observed over the western part of the IRBs in the last four decades
- West and North-east flowing river basins were found to be highly flood-prone regions resulting in vulnerable hazards

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract During recent decades, India experienced more frequent and severe floods due to increasing extreme rainfall events over different Indian River Basins (IRBs). The present study uses Generalized Extreme Value distribution, Expert Team on Climate Change and Detection Indices, and Standardized Precipitation Index to examine the trend in extreme rainfall events over the IRBs using long-term observed high-resolution gridded rainfall data (1901-2019) obtained from India Meteorological Department. The analysis depicts a marked shifting trend in extreme rainfall events from northeastern Indian river basins toward the western Indian river basins during the recent decades of 1981-2019. The spatial variations in the annual maximum rainfall for the 10-, 30-, and 100-year return levels show statistically significant increasing trends over the IRBs. The observed decadal changes of rainfall during wet and dry conditions showed the shifting and increasing (15%–58.74%) pattern in extreme rainfall events during the last decades of the 20th and current twenty first century over the west-flowing river basins. This research highlights the significant increasing trend in extreme rainfall events, which may pose a grave risk to agriculture, human life, and infrastructure, predominantly on the vulnerable sections of the society.

1. Introduction

In the wake of recent global warming, an increase in extreme weather events such as extreme rainfall is observed globally, which has a severe impact on natural and man-made ecosystems (IPCC, 2014; Libertino et al., 2019; Papalexiou & Montanari, 2019). In recent decades, it was observed that around 20 to 80 million of the global population is affected by floods every year, whereas India has observed the most significant loss to life and property due to extreme rainfall events (EM-DAT, 2019). More than 279 reported flood events in India from 1953 to 2018, affecting about 2.167 billion population, killing more than one lakh people, and causing damage to

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