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Spatio-temporal and trend analysis of rain days having different intensity from 1901 – 2020 at regional scale in Haryana, India

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A R T I C L E I N F O

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A B S T R A C T

Our study has investigated spatio-temporal distribution of rainfall and rain day trends during different seasons for all districts of Haryana, India. Gridded rainfall dataset of 120 years (1901 to 2020) from India Meteorological Department (IMD) was analysed using mean rainfall, rainfall deviation, seasonal rainfall ratio (SRR), coefficient of variation (CV), number of rain days, rainfall intensity, trends of rain days, Empirical Orthogonal Functions (EOF) and Principal Component (PC) analysis. Districts lying in eastern Haryana have experienced more rainfall (less variability) than the ones lying in western Haryana during each season. SRR and CV analysis depicted most consistent rainfall during monsoon and maximum variability during post-monsoon season. Highest number of rain days was observed during monsoon season followed by pre-monsoon, winter and post-monsoon season in Haryana. Innovative trend analysis method (ITAM) shows a declining trend in number of rain days during winter and post-monsoon season while an increasing trend was observed during pre-monsoon season. Overall, monsoon season has shown a falling trend in moderate while rising trend was observed in both light and heavy rainfall intensity categories in most of districts. Dominant EOF explained maximum variability during post-monsoon season followed by winter, pre-monsoon, and monsoon season, respectively. PC analysis captured inter-annual variability in rainfall during each season. Our findings highlight qualitative and quantitative aspects of seasonal rainfall dynamics at districts level. This study is beneficial in understanding impact of climate change and climate variability on rainfall dynamics in Haryana which may guide policymakers and beneficiaries in optimizing use of hydrological resources.

1. Introduction

Rainfall distribution patterns have altered across the globe because of climate variability and climate change resulting from the increase in the concentration of greenhouse gases (GHGs) in the atmosphere due to anthropogenic activities (Gergis and Henley 2017; Deng et al. 2019; Singh et al. 2019). One of the most challenging climatological tasks is to identify the presence of climate change and quantify the extent of its magnitude. Any shift in this critical hydro-climatic variable's behaviour is not evenly distributed all over the region; rather, it has its own distinct local component (Bisht et al. 2018). Scientists across different parts of the world have conducted research on climate change to define rainfall dynamics at regional to local level and attempted to decipher the trajectory of various climate indices (Singh 2018a; Talchabhadel and Karki 2019; Tito et al. 2020; de Oliveira-Júnior et al. 2021; Ferreira et al. 2021; Teixeira et al. 2021). The analysis of prevailing trends in climate conditions using long-term meteorological data is a crucial element for studying the impact of climate change. Based on the historical records of meteorological stations, the majority of identified trends have been centred on rainfall and temperature indices. Droughts and declining rainfall are likely to continue as a consequence of rising global temperatures over the last century (Cook et al. 2014; Gizaw and Gan 2017; Carrão et al. 2018). Extreme climatic events like heat and cold waves, flooding and drought, have serious repercussions on the health of humans, animals, the environment as well as economy (Handmer et al. 2012). Changing rainfall volumes and distribution is

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one of the major consequences of climate change (Dore 2005; Van Wageningen and Du Plessis 2007; Trenberth 2011), which requires urgent consideration and systematic research. Being one of the vital elements of the hydrological cycle the comprehensive understanding of long-term rainfall distribution and trends in intensity and number of rainy days is necessary.

The previous studied by many researchers (Smith, 2004; Joshi and Rajeevan, 2006; Guhathakurta and Rajeevan, 2008; Kumar et al., 2010; Subash et al., 2011; Tabari et al., 2011; Patra et al., 2012; Singh and Borah, 2013; Taxak et al., 2014; Gajbhiye et al., 2016; Singh, 2018b; Dwivedi et al., 2019; Malik and Kumar, 2020) give insights about the spatio-temporal distribution of rainfall and variability in hydro-meteorological time series with respect to climate change in Indian context. Several studies show a rise in the frequency of intense rainfall events in many parts of Indian subcontinent while a decrease in number of rainy days and total annual precipitation (Sinha Ray and Srivastava, 2000; Lal, 2003, Goswami et al., 2006; and Dash et al., 2007, 2009). Rainfall analysis carried out by Pal and Al-Tabbaa (2011) for a period of 1954–2003 showed a decreasing trend during the spring and monsoon rainfall while increasing trends were noticed during autumn and winter rainfall over India. Decreasing trends in rainfall over central India, while increasing trend at southern peninsular and northeast India were reported by Lacombe and McCartney (2014). Significantly increasing trends in annual rainfall were reported by Subash and Sikka (2014) while analysing rainfall data for a period of 100 years from 1904 – 2003 at meteorological sub-divisions level in India, whereas Mondal et al. (2015) observed decreasing trends over entire India from 1871 to 2011. A number of researchers have conducted studies on rainfall trends for different states and regions of India like Assam (Goyal, 2014), Bundelkhand region (Jana et al., 2017), Chhattisgarh (Dandodia and Sastri, 2015; Meshram et al., 2017), Haryana (Chauhan et al., 2022), Himachal Pradesh (Jaswal et al., 2015), Jharkhand (Chandniha et al., 2017; Sharma and Singh, 2017), Kerala (Krishnakumar et al., 2009; Nair et al., 2014), Madhya Pradesh (Duhan and Pandey, 2013), Odisha (Patra et al., 2012), Punjab (Kaur et al., 2021), Rajasthan (Pingale et al., 2014; Mundetia and Sharma, 2014), Uttarakhand (Malik and Kumar, 2020), West Bengal (Ghosh, 2018) and western Himalayas (Singh and Mal, 2014) using different trend analysis methods and observed a variety of results at regional scale.

Many researchers have also analysed rainfall trends over Haryana like Guhathakurta et al. (2020) examined the monthly, seasonal and annual data series of 30 years (1989–2018) for all districts of Haryana and found a significantly decreasing trend in Ambala, Bhiwani, Charkhi Dadri, Kaithal, Panchkula and Panipat. Nain et al. (2019) performed trend analysis at monthly scale for 27 rain gauge stations scattered in all the districts of Haryana State using datasets of IMD Pune for a period of 42 years (1970-2011) and reported mixed trends for stations. Malik and Singh also (2019) explored rainfall pattern characteristics in the Haryana region during (1997–2014) at daily and seasonal scale and found positive trend in monthly maximum and total rainfall. Anurag et al. (2018) performed monthly analysis of rainfall and reported variable results with somewhat increasing trends at Hisar and decreasing trends at Sirsa district in Haryana state. There are many other studies conducted on small scales for the study area which have used different approached to detect trends in rainfall like by Sharma and Jain (2017) for Sirsa district, Anurag et al. (2017) for Hisar district, Bemal et al. (2012) over eastern agroclimatic zone of Haryana. The trend analysis of historical rainfall data provides understandings of the local rainfall characteristics at the regional level and assists policymakers in drawing up effective hydrological strategies to tackle drought and reduce flood risk with the proper management of water resources. For doing so we have used innovative trend analysis method (ITAM), which is a novel and robust method of trend detection and various investigations have effectively applied ITAM to quantify the trends in hydro-meteorological variables like rainfall (Cengiz et al., 2020; Ay and Kisi, 2015; Ahmad et al., 2018), temperature (Serencam, 2019), drought variables (Tosunoglu and Kisi, 2017), evapotranspiration (Kisi, 2015), and water quality parameters (Kisi and Ay, 2014; Markus et al., 2013) across the globe. However, there are no previous investigations which have used ITAM to detect trends of rain days on intensity basis on a century long time series of rainfall in Haryana.

Haryana is one of leading state in agricultural production and serves as a pillar in ensuring food security of the nation. Henceforth, Haryana is termed as the breadbasket of India because of the sustained agricultural production in the state (Kumar et al., 2018; Shirsath et al., 2020), primarily producing paddy during Kharif and wheat during the Rabi season. But there are emerging challenges in Haryana due to which agriculture is becoming non-profitable such as higher cost of inputs including water for irrigation and its allocation. Being one of the major paddy-producing states of the country (Sihmar, 2014; Nirmala and Muthuraman, 2016; Singh, 2018), the groundwater table in Haryana, has dropped severely in the recent decades at an average rate of 4.0 ± 1.0 cm yr^{-1} (Kumar et al., 2007; Chaudhuri and Roy, 2016). Owing to these alarming situations, there is a dire need to monitor the water supplies of Haryana State by recognizing the shifting rainfall patterns for proper and timely allocation of funds or necessary inputs, adequate implementation of the contingency plans in case of water scarcity, preparedness for the hostile weather events like floods and droughts, maintaining the water resources for sustaining agricultural production round the year. The rationale behind selecting the district as an administrative unit in this study is to capture the spatio-temporal patterns of seasonal rainfall because inadequate and irregular rainfall in many parts of Haryana is one of the key limitations to agricultural and other socio-economic activities in the state. However, very limited investigations concentrating on spatio-temporal dynamics of seasonal rainfall have been conducted across the entire state at the district level. Due to the uneven distribution of rainfall and the mismatch between water availability and demand, the analysis of trends in rain days in different categories based on the intensity is also very much needed for agriculture and water resource management. No study has been conducted previously, where the trends in rain days have been analysed at district level in Haryana, India. A detailed analysis of observed trends in the rain days in three different categories, viz. light, moderate and heavy rainfall intensity at district level in Haryana, India as shown in Fig. 11 was also carried out to identify the region of significant changes. This may help policymakers to locate the potential drought and flood-prone areas at micro-level in order to take effective management of the available resources and to take appropriate and timely socio-economic decisions across the state. In the light of the discussion made previously, the objectives of this study were to analyse the distribution pattern, variability and trends in rain days for different season using rainfall time series data of 120 years (1901–2020) for all 22 districts of Haryana, India. This paper is divided into five parts. Section 2 offers a description of the study area and data used. Methodology, and results and discussions, are addressed in Sections 3 and 4, respectivelyy. Section 5 outlines the conclusions derived from the study.

2. Study area and data

The study area comprises 22 districts of Haryana, as shown in Fig. 1. Haryana is located in north-western India and occupies about 1.3 percent of the geographical area of the country. Latitudinal and longitudinal coverage of state extends from 27°39′ to 30°35′ N and 74°28′ to 77°36′ E, respectively, with a geographical area of about 44,212 km^2 and altitude ranging from 100 meters to 1500 meters and with a mean altitude of 238 meters above mean sea level. Among districts, Panchkula has the highest mean elevation of 506 meters, whereas the lowest mean elevation of 192 meters is of Palwal.

In the present study, daily rainfall for the period of 1901-2020 (120 years) generated by the India Meteorological Department (IMD) at a grid resolution of 0.25×0.25 degree, was directly projected on the district shapefile of Haryana state and the zonal-statistical average of the bound

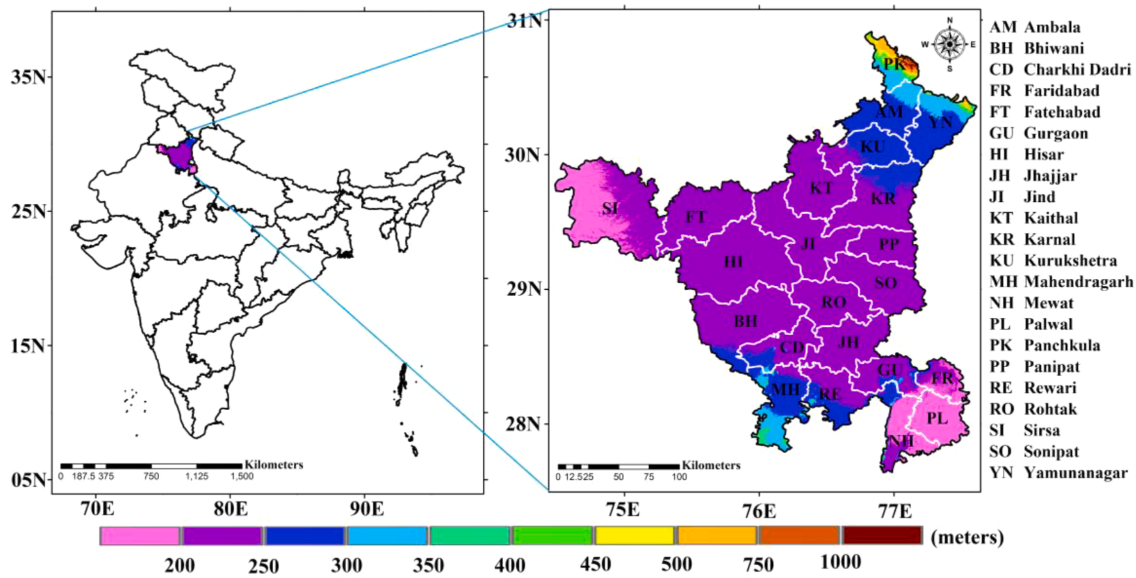

Fig. 1. Study area showing districts of Haryana based on SRTM DEM based elevation.

district region was processed and used for the analysis. This high-resolution gridded dataset was developed using daily rainfall data records collected from a network of 6955 rain gauge stations over India by Pai et al. (2014).

3. Methods

Urbanization in India started to intensify post-independence in 1947 (Khan, 2011). In India, the Green Revolution began in the 1960s, and it refers to an era when traditional agriculture was getting transformed into an industrial system due to the adoption of modern methods and technologies such as the introduction of seeds of high yielding varieties (HYV), tractors, irrigation facilities, pesticides, and fertilizers to increase food production in order to alleviate hunger and poverty. Following a clear shift towards economic liberalisation in the 1980s, the Indian economy has grown remarkably because of increased industrialisation (Nomura, 2019), but high-intensity agriculture during the green revolution was heavily dependent on the use of pesticides and chemical fertilizers, particularly the ones containing nitrogen. Since 1960, the usage of nitrogenous fertilizers has increased by many folds globally (Tilman, 1998 and Davidson, 2009). Such rapid urbanization, industrialization, and intensive agricultural activities since the green revolution

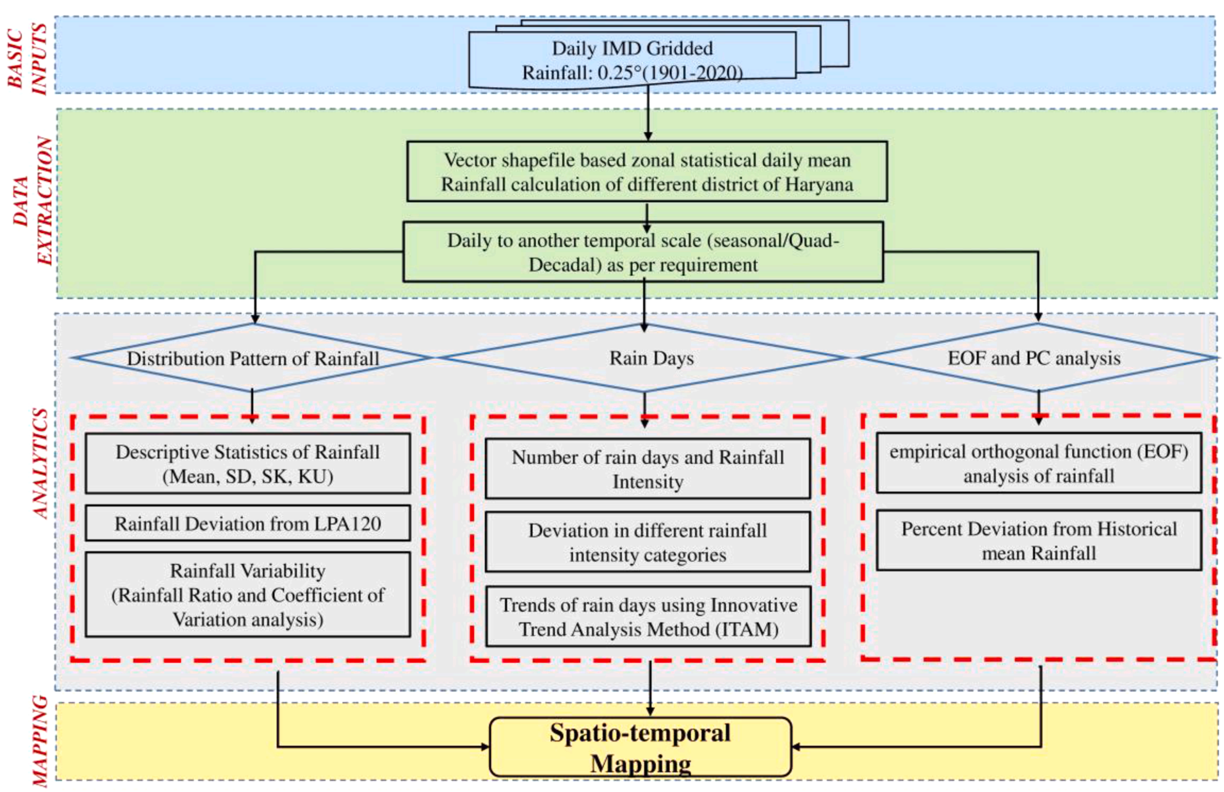

Fig. 2. The schematic flow chart of the methodology.

are recognized as the possible reason for changing rainfall patterns and extreme events. Haryana served as the epicenter of the green revolution in India (Kasliwal, 2021; Saha and Loveridge, 2020). Based on this background, we sliced the period of 120 years into 3 quad-decadal times (QDT) intervals of 40 years each viz; QDT1, QDT2 and QDT3 for analysing rainfall distribution and variability where QDT1 corresponds to pre-urbanization era (1901–1940), QDT2 corresponds to accelerated industrialization, urbanization and green revolution era (1941-1980) and QDT3 corresponds to recent climate (1980–2020).

IMD has defined four meteorological seasons over India which are *viz:* winter (January-February), pre-monsoon (March-May), monsoon (June-September), and post-monsoon (October-December). The daily data of each district were further cumulated over these seasons to obtain the total seasonal rainfall. Basic statistical analysis including mean, deviation of rainfall in per cent (DRP), number of rain days, rainfall intensity, trend detection with Innovative trend analysis etc. of seasonal rainfall were used to compare and visualize the time series data (Fig. 2).

3.1. Distribution patterns of rainfall

The normal seasonal rainfall for each district was calculated as long period average rainfall by taking the average of rainfall for the whole study period of 120 years (hereafter referred as LPA120). The seasonal rainfall deviation at a district during each QDT1, QDT2 and QDT3 was calculated by expressing the seasonal rainfall in terms of the per cent departure from LPA120, and is termed as deviation of rainfall in per cent (DRP). Positive DRP indicates above-normal rainfall, whilst negative DRP indicates below-normal rainfall, during that particular QDT.

$$DRP = \left(\frac{R_{QDT} - LPA120}{\mathrm{LPA120}}\right) \times 100 \quad \text{(i)}$$

Where, DRP is the deviation of rainfall in per cent, R_{QDT} is the seasonal rainfall of the district during any QDT, LPA120 is the climatological long term mean rainfall of 120 years (1901-2020).

3.2. Variability of Rainfall

The coefficient of variation (CV) is a statistical measure of dispersion of values around the mean in a time series. It represents the ratio of the standard deviation to the mean, and is a useful tool to compare the degree of variation in one rainfall time series from another, even if their mean rainfall are drastically different from each other. CV of seasonal rainfall was calculated by using the following expression:

$$\mathrm{CV} = \frac{\mathrm{SD}}{\mathrm{LPA120}} \times 100 \quad \text{(ii)}$$

Where, CV is the coefficient of variation of seasonal rainfall in per cent, SD is the standard deviation of seasonal rainfall and LPA120 is the climatological long term mean rainfall of 120 years (1901-2020).

The variability of rainfall at any location may also be brought out by a simple ratio of rainfall. The seasonal rainfall ratio (SRR) is defined as the difference between the maximum and minimum rainfall of the seasonal rainfall time series expressed in terms of mean. SRR was calculated by using the following expression:

$$SRR = \left(\frac{R_{max-}R_{min}}{P_{mean}}\right) \times 100 \quad \text{(iii)}$$

Where, SRR is the seasonal rainfall ratio, R_{max} is the maximum rainfall, R_{min} is the minimum rainfall and LPA120 is the climatological long term mean rainfall of 120 years (1901-2020). This SRR shows the stability of rainfall with special relationship. Higher the SRR, higher is the variability of rainfall and vice versa (Rathod and Aruchamy, 2010). The CV and SRR were worked out to visualize the spatio-temporal patterns of seasonal rainfall variability over Haryana during the study period of 1901 to 2020.

3.3. Number of rain days and rainfall intensity

A day is considered as 'rain day' if the amount of rainfall occurred on that day is 0.1 mm or more (Guhathakurta, et al., 2011). The average number of rain days for all the districts of Haryana was computed over the whole study period of 120 years (1901–2020) during different seasons. To study the spatio-temporal changes in the frequency of rainfall events, rain day events based on the daily rainfall intensity (RI) i.e. amount of rainfall happened in a single day during different seasons were classified as light (0.1 to 15.5 mm), moderate (15.6 to 35.5 mm) and heavy (35.6 mm and above) according to India Meteorological Department. Per cent deviation in the intensity of rainfall events during different season at district level in different QDTs against the long-term mean of rainfall events in 120 years in that specific category was also worked out for studying spatio-temporal variation in different RI categories.

3.4. Trends of rain days

The non-parametric Innovative trend analysis method (ITAM) (Şen, 2012) was implemented to identify the trends in rain days. ITAM is proficient to identify the monotonic and sub-trends in the time series (Pour et al. 2020). ITAM does not have assumptions such as serial normality, autocorrelation, outliers, and data length. To perform ITA, the time series of rain days in different categories viz. light, moderate and heavy rainfall was prepared for different seasons from original rainfall series based on the daily rainfall intensity. These time series were then first split into two equal parts from start to the end date, then the bifurcated sub-series were arranged in ascending order. The first half of the series (X_i) was positioned at X-axis, and the second half of the series (Y_i) was positioned on the Y-axis of the Cartesian coordinate system. Data lying on the 45° line (1:1), are indicative of no trend in the time series. Data located above the 45° line indicates an upward trend, while the data situated below the 45° line indicates a downward trend. The innovative trend indicator (ITI) of ITAM as proposed by proposed by Şen (2017) was estimated using the following equation:

$$\mathrm{ITI} = \frac{1}{n}\sum_{i=1}^{n}\frac{10(X_i - Y_i)}{\overline{X_i}} \quad \text{(iv)}$$

Where, ITI is the innovative trend indicator, n is the number of observations in the time series, X_i is the first half of the time series (where i = 1, 2, 3,..........n/2), Y_i is the second half of the time series (where i = n/2 + 1, n/2 + 2,..........n) and $\overline{X_i}$ is the mean of first half of the time series. A positive value of ITI indicates an increasing trend. However, a negative value of ITI indicates a decreasing trend. In this study, the null hypothesis (no trend) was tested against the alternate hypothesis (there is a trend in the data) at two different significance levels (α), i.e., α = 5% and α = 1%.

3.5. EOF and PC analysis of rainfall

Empirical Orthogonal Functions (EOF) is one of the most effective tools for describing the spatio-temporal variability of meteorological fields, which explain maximum variability with the constraints of orthogonality. We have used EOF analysis to determine the spatial-temporal variability in rainfall time series of Haryana during different seasons. As the EOF extracts the dominant modes of variability via singular decomposition of time series datasets of meteorological variable, the EOF analysis linearly transforms this datasets into a newly projected coordinate system, which are usually known as Eigenvectors or basis vectors, orthogonal to each other. The selection of Eigenvectors is based on the magnitude of variability carried by them, and the first Eigenvector (EOF1) generally carries the maximum possible variability in the time series. The EOF analysis finds applications in various climate-related research (Geetha and Raj, 2014; Giles et al., 2020; Irving and

Simmonds, 2016; Mastrantonas et al., 2021; Dar and Dar, 2021). The governing methodology of EOF analysis (Obukhov, 1947; Lorenz, 1956; Craddock., 1973) is explained below. The data set is in a three-dimensional field, a function of grid and time, and is represented as:

$$\mu_{xyz} = f(\Delta_i, \phi_j, \lambda_k) \quad \text{(v)}$$

Where, Δ_i represent time (i = 1, 2, 3,……….. to n), ϕ_j, represent latitude (j = 1, 2, 3,……….. to m_1) and λ_k, represent longitude (k = 1, 2, 3,……….to m_2) with conditions $n \geq i \geq 1$, $p_1 \geq j \geq 1$ and $p2 \geq k \geq 1$. After conjugating the latitude and longitude in space, a two-dimensional matrix Q is obtained with a grid size of $m = m_1 \times m_2$ which is given as:

$$Q = \begin{bmatrix} q_{11} & q_{12} & \cdots & \cdots & \cdots & q_{1m} \\ q_{21} & q_{22} & \cdots & \cdots & \cdots & q_{2m} \\ \vdots & \vdots & & & & \vdots \\ \vdots & \vdots & & & & \vdots \\ \vdots & \vdots & & & & \vdots \\ q_{n1} & q_{n2} & \cdots & \cdots & \cdots & q_{nm} \end{bmatrix}. \quad \text{(vi)}$$

The 2-dimensional spatial data of rainfall was converted to a 3-dimensional dataset after stacking layer by layer of different years from 1901 to 2020 for each season for a period of 120 years for further analysis. The time average of the climate variable field at j^{th} grid point was estimated as:

$$q_j = \frac{1}{n}\sum_{k=1}^{n} q_{kj} \quad \text{(vii)}$$

The mean of the climateariable field is given by:

$$\overline{Q} = (\overline{q_{.1}}, \overline{q_{.2}}, \overline{q_{.3}} \ldots\ldots\ldots\ldots \overline{q_{.m}}) \quad \text{(viii)}$$

Therefore, the anomaly field is calculated as the difference between the original data Q and the mean of the field as is given as:

$$\overset{'}{Q} = Q - 1\overline{Q} = \left(1 - \frac{1}{n}\, 11^{\Delta}\right) Q \quad \text{(ix)}$$

Where, 1 is all-ones column vector matrix. Due to the spatial arbitrariness of the climatic variables over the earth's surface, the actual structure of EOF patterns may get influenced. Therefore, to evaluate the correct EOF structures, the data matrix is usually weighted before further analysis. Before computing EOFs, the most efficient weighting strategy is to weigh the data points by the square-root of cosine of the corresponding latitude. For the latitude ϕ_k of k^{th} grid point, the diagonal matrix D_ϕ is represented as:

$$D_\phi = Diag[\cos\phi_1, \quad \cos\phi_2, \quad \ldots\ldots\ldots \cos\phi_m] \quad \text{(x)}$$

And the weighted anomaly matrix is computed as:

$$Q_w = \overset{'}{Q} D_\phi \quad \text{(xi)}$$

After weighing the matrix, EOFs in this study for each season were estimated in two ways: (a.) EOF expressed as the correlation between the principal component time series (PC) and the time series of the EOF input dataset at each grid point, (b.) EOF expressed as the covariance between the PC time series and the time series of the EOF input dataset at each grid point. The main purpose of EOF analysis is to find the linear combination of all the variables (grid points) that explain the maximum amount of variance. A variety of software tools were used in generating the main results presented in this paper. Simple editing of GRD gridded datasets of rainfall to NetCDF was performed using a collection of command line utilities known as the Climate Data Operators (CDO), while a Python based package-management system called "PIP" was used for complex data analysis and visualization. With respect to specific Python libraries, "netCDF4" was used for data analysis and the reading/writing of netCDF files (Rew et al., 2006; Lee et al., 2008; Delaunay et al., 2019), which is a library that builds upon the Numerical Python ("NumPy"; van der Walt et al., 2011), "HDF5" and "Cython". Similarly "Cartopy", "Geopandas" and "Matplotlib" were used for plotting of the figures. "eofs" python library (Dawson, 2016) was used for EOF and PC analysis.

4. Results and discussions

4.1. Distribution pattern of rainfall

Descriptive statistical parameters including mean rainfall, standard deviation, skewness and kurtosis in seasonal time series rainfall data of 22 districts of Haryana through the course of 120 years are summarized in Table 1. The mean rainfall for Haryana state during the entire study period was 37.0 mm, 37.7 mm, 468.3 mm, and 24.8 mm, whereas standard deviation was found to be 24.8 mm, 28.8 mm, 136.9 mm, and 29.4 mm during winter (JF), pre-monsoon (MAM), summer monsoon (JJAS) and post-monsoon (OND) season, respectivelyy. The skewness for rainfall in Haryana was found to be 0.8 in winter, 1.7 in pre-monsoon, 0.3 in monsoon and 2.5 in post-monsoon. This illustrates the positive skewness in all the seasons where mode is always higher than mean and median value of the datasets. The values for kurtosis are 0.3 in winter, 3.9 in pre-monsoon, -0.2 in monsoon and 7.6 in post-monsoon. Among different districts, the values of mean rainfall and standard deviation for winter rainfall events ranged from 21.0 mm (Mahendragarh) to 125.0 mm (Panchkula) and 20.1 mm (Sirsa) to 76.0 mm (Panchkula), respectively. The values of mean rainfall and standard deviation for the pre-monsoon rainfall ranged from 22.9 mm (Faridabad) to 118.6 mm (Panchkula) and 23.7 mm (Sirsa) to 81.5 mm (Panchkula), respectively. The mean rainfall of the summer monsoon season varied from 259.8 mm (Sirsa) to 1061.0 mm (Panchkula) with standard deviation varying between 118.4 mm (Sirsa) and 318.3 mm (Panchkula). In the post-monsoon season, mean rainfall varied from 15.5 mm (Sirsa) to 74.4 mm (Panchkula) with standard deviation varying between 22.6 mm (Charkhi-Dadri) and 87.8 mm (Panchkula).

The spatio-temporal variation of mean rainfall at the district level in the state of Haryana during different seasons is depicted in Fig. 3. During winter season, the highest mean rainfall of nearly more than 80 mm was observed in the districts lying in the north-eastern region of Haryana *viz;* Yamunanagar, Ambala and Panchkula, whereas the lowest amount of mean rainfall was observed in the districts lying in the south-western region of the state *viz;* Mahendragarh, Charkhi Dadri, Mewat and Sirsa of less than 25 mm. The highest mean rainfall during the pre-monsoon season was observed in the districts lying in the north-eastern region of Haryana *viz;* Panchkula, Ambala, and Yamunanagar with a value above 60 mm, whereas the lowest amount of mean rainfall was observed in the districts lying in the western region of the state *viz;* Mahendragarh, Charkhi Dadri, Sirsa, Palwal, Mewat and Faridabad with a value less than 30 mm. The highest mean rainfall during the monsoon season was observed in the districts lying in the north-eastern region of Haryana *viz;* Panchkula, Yamunanagar and Ambala with a value above 850 mm, whereas the lowest amount of mean rainfall was observed in the districts lying in the western region of the state *viz;* Sirsa, Fatehabad, Hisar and Charkhi Dadri with a value less than 350 mm. During post-monsoon season, the highest mean rainfall of nearly more than 45 mm was observed in the districts lying in the north-eastern region of Haryana *viz;* Panchkula, Yamunanagar and Ambala whereas the lowest amount of mean rainfall was observed in the districts lying in the western region of the state *viz;* Sirsa, Charkhi Dadri, Mahendragarh, Bhiwani, Fatehabad, Hisar having a value below 20 mm. The comparatively higher rainfall in the north-eastern and eastern parts of Haryana may be attributed to comparatively their higher elevation than the western parts (Singh and Kumar, 1997; Kuraji et al., 2001; Shrestha et al., 2012).

4.2. Rainfall deviation

Fig. 4 portrays the visuals of spatio-temporal variation of deviation of

Table 1
Descriptive statistics of seasonal rainfall in different districts of Haryana, India during 1901-2020.

District	Winter				Pre-monsoon				Monsoon				Post-monsoon			
	Mean	SD	SK	KU	Mean	SD	SK	KU	Mean	SD	SK	KU	Mean	SD	SK	KU
Ambala	79.8	52.3	1.1	1.6	65.8	50.8	2.1	6.5	863.0	262.2	0.6	0.4	47.9	54.0	2.0	5.0
Bhiwani	25.5	22.1	1.2	1.3	30.7	25.9	1.6	3.1	352.9	136.4	0.6	0.1	17.7	24.0	2.3	6.0
Charkhi Dadri	22.0	21.3	1.3	1.5	27.9	27.8	1.8	3.9	343.7	158.5	0.6	0.1	16.1	22.6	2.3	5.3
Faridabad	27.5	28.1	1.3	0.9	22.9	27.2	2.1	5.4	520.0	265.2	0.9	0.8	24.7	41.1	2.7	8.0
Fatehabad	26.9	21.0	1.1	0.9	33.2	28.0	1.4	2.6	307.3	135.3	0.6	0.0	18.2	28.3	3.5	16.5
Gurgaon	29.8	23.3	0.8	-0.2	37.5	37.7	2.1	5.1	514.4	182.9	0.4	-0.6	24.0	35.2	3.4	15.3
Hisar	27.6	23.3	1.3	1.5	35.5	27.9	1.2	1.0	336.7	135.3	0.6	0.0	18.5	27.5	2.8	9.3
Jhajjar	26.0	21.6	1.2	1.4	31.7	31.3	1.7	2.8	429.0	168.5	0.5	-0.1	19.0	27.4	2.9	10.6
Jind	33.2	29.2	1.5	2.4	34.7	30.4	1.5	2.2	388.4	150.8	0.7	0.5	19.6	26.9	2.4	6.2
Kaithal	43.4	32.5	0.8	-0.1	41.6	36.0	1.7	3.1	441.9	166.9	1.0	2.2	24.0	31.8	2.5	7.3
Karnal	46.3	34.8	1.2	1.5	38.4	33.6	1.9	4.4	529.1	173.2	0.4	-0.1	28.6	37.9	2.6	9.0
Kurukshetra	56.1	38.0	0.7	0.1	48.3	40.9	1.9	4.6	591.4	181.6	0.5	0.6	34.7	42.3	2.2	5.2
Mahendragarh	21.0	22.2	1.4	1.4	29.3	27.9	1.5	2.0	396.5	164.3	0.8	0.9	16.8	22.9	2.0	3.8
Mewat	22.9	20.9	1.4	2.3	25.8	27.5	1.8	3.2	480.5	172.2	0.6	0.3	22.8	36.5	3.4	14.6
Palwal	26.0	22.8	1.1	0.8	25.9	29.3	1.9	3.2	487.9	185.6	0.6	0.2	26.7	45.8	3.7	18.5
Panchkula	125.0	76.0	1.1	1.6	118.6	81.5	1.7	5.0	1061.1	318.3	0.2	0.0	74.4	87.8	2.7	9.7
Panipat	40.5	32.8	1.3	1.9	35.7	36.0	2.4	8.3	549.9	219.8	0.4	-0.5	29.1	44.3	3.2	14.1
Rewari	25.6	23.7	1.4	2.3	33.3	34.6	1.7	2.9	456.4	172.3	0.7	0.9	20.5	27.2	2.0	4.2
Rohtak	31.0	27.0	1.5	3.6	36.9	33.7	2.0	5.0	417.8	163.0	0.6	0.7	21.1	25.2	1.7	2.7
Sirsa	23.3	20.1	1.0	0.4	27.7	23.7	1.2	1.2	259.8	118.4	1.1	3.0	15.5	26.2	4.8	32.3
Sonipat	37.1	28.2	1.1	1.6	39.2	35.9	2.3	7.5	488.1	173.5	0.6	0.0	24.6	32.5	2.7	10.9
Yamunanagar	78.1	54.5	1.0	0.6	62.3	47.0	1.5	2.1	935.0	267.8	-0.1	-0.6	48.3	58.2	3.0	12.9
Haryana	37.0	24.8	0.8	0.3	37.7	28.8	1.7	3.9	468.3	136.9	0.3	-0.2	24.8	29.4	2.5	7.6

Where, SD = Standard Deviation; SK = Skewness; KU = Kurtosis

rainfall in percent (DRP) at the district level for each season in different QDTs against LPA120. The positive DRP depicts above-normal rainfall and the negative DRP depicts below normal rainfall. During QDT1 in the winter and post-monsoon season, it was found that most of the districts got above-normal rainfall, whereas, most districts have experienced below-average rainfall throughout the pre-monsoon and monsoon seasons. The below normal rainfall trend was prevalent during QDT2 and QDT3 in winter season. During the last QDT, pre-monsoon season rainfall has shown a rising trend, however the most negative deviations were noted in QDT2. The decrease in rainfall in recent years is apparent over most of the districts during the winter, summer monsoon, and post-monsoon seasons as depicted by the negative DRP during the QDT3. Overall, no synchronized trend of deviation was observed in the all three QDTs during any particular season. Rainfall during winter and pre-monsoon season have shown positive rainfall deviation in all districts during QDT1 and QDT3, respectively. However, both monsoon and post-monsoon season have shown a positive trend of rainfall deviation in all districts during QDT2. Overall, we can conclude that rainfall is decreasing during winter, monsoon and post-monsoon season while increasing in pre-monsoon season in the last QDT i.e., during recent climate. This change in rainfall pattern can be due to the high rate of climate change during recent years (Dore 2005; Patra et al. 2012).

4.3. Rainfall variability

The spatial variability in the seasonal rainfall of Haryana over the course of the study period is expressed by seasonal rainfall ratio (SRR) and coefficient of variation (CV) in Fig. 5. A larger value of SRR as well as CV is indicative of large spatial variability and vice-versa. The value of both SRR and CV was observed highest during post-monsoon, while the values were lowest for monsoon season. Among districts, the variability of rainfall was higher in the districts lying in western Haryana, as compared to the districts lying in eastern part of Haryana. However, rainfall during each season in the entire state showed variability, but the magnitude and range of SRR as well as CV was widest during the winter and narrowest during the monsoon season. Overall, the most consistent rainfall was observed during the monsoon season in the districts lying in north-eastern region of Haryana.

4.4. Number of rain days and rainfall intensity

The spatio-temporal variation in the number of rain days at the district level for a period of 120 years from 1901 to 2020 in Haryana during different seasons is depicted in Fig. 6. During the winter season, the average number of rain days over Haryana varies from nearly 5 in Rewari to more than 13 in Panchkula. The districts lying in western Haryana viz; Rewari, Charkhi-Dadri, Faridabad, Mahendragarh, Palwal, Mewat, and Sirsa on average received less than 6 rain days, while the districts lying in eastern Haryana viz; Yamunanagar, Ambala, and Panchkula received more than 10 rain days during the winter season. The average number of rain days in Haryana during the pre-monsoon season ranges from approximately 6 in Faridabad to more than 18 in Panchkula. The districts lying in south-eastern Haryana viz; Faridabad, Rewari, and Palwal on average received less than 8 rain days, while the districts lying in northeastern Haryana viz; Kurukshetra, Yamunanagar, Ambala, and Panchkula have received more than 12 rain days during pre-monsoon season. The average number of rain days during the monsoon season in Haryana varies from nearly 41 at Sirsa to more than 74 at Panchkula. Districts lying in north-western Haryana viz; Sirsa, Rewari, Charkhi Dadri, Hisar, and Fatehabad received less than 46, while districts lying in northeastern Haryana viz; Yamunanagar, Panchkula, and Ambala have received more than 70 rain days during monsoon season days. During the post-monsoon season in Haryana, the average number of rain days ranges from about 3 in Rewari to over 7 in Panchkula. Overall the maximum number of rain days was observed during the monsoon season followed by pre-monsoon, winter, and post-monsoon season in Haryana at seasonal scale. However, districts lying in eastern Haryana received higher number of rain days as compared to the ones lying in western Haryana in each season.

The spatio-temporal variation in the frequency of rainfall events based on rainfall intensity (RI) for each season was worked out at the district level in Haryana. For doing so, total number of rainy days in a season was broken down into different rainfall categories depending upon the daily rainfall intensity (RI) i.e. the amount of rainfall that happened in a single day and classified as light (0.1 to 15.5 mm), moderate (15.6 to 35.5 mm) and heavy (35.6 mm and above) during different seasons as per the classification given by India Meteorological Department and the results thus obtained are depicted in Fig. 7. Light, moderate, and heavy rainfall intensity were observed in 78.0 – 96.0%,

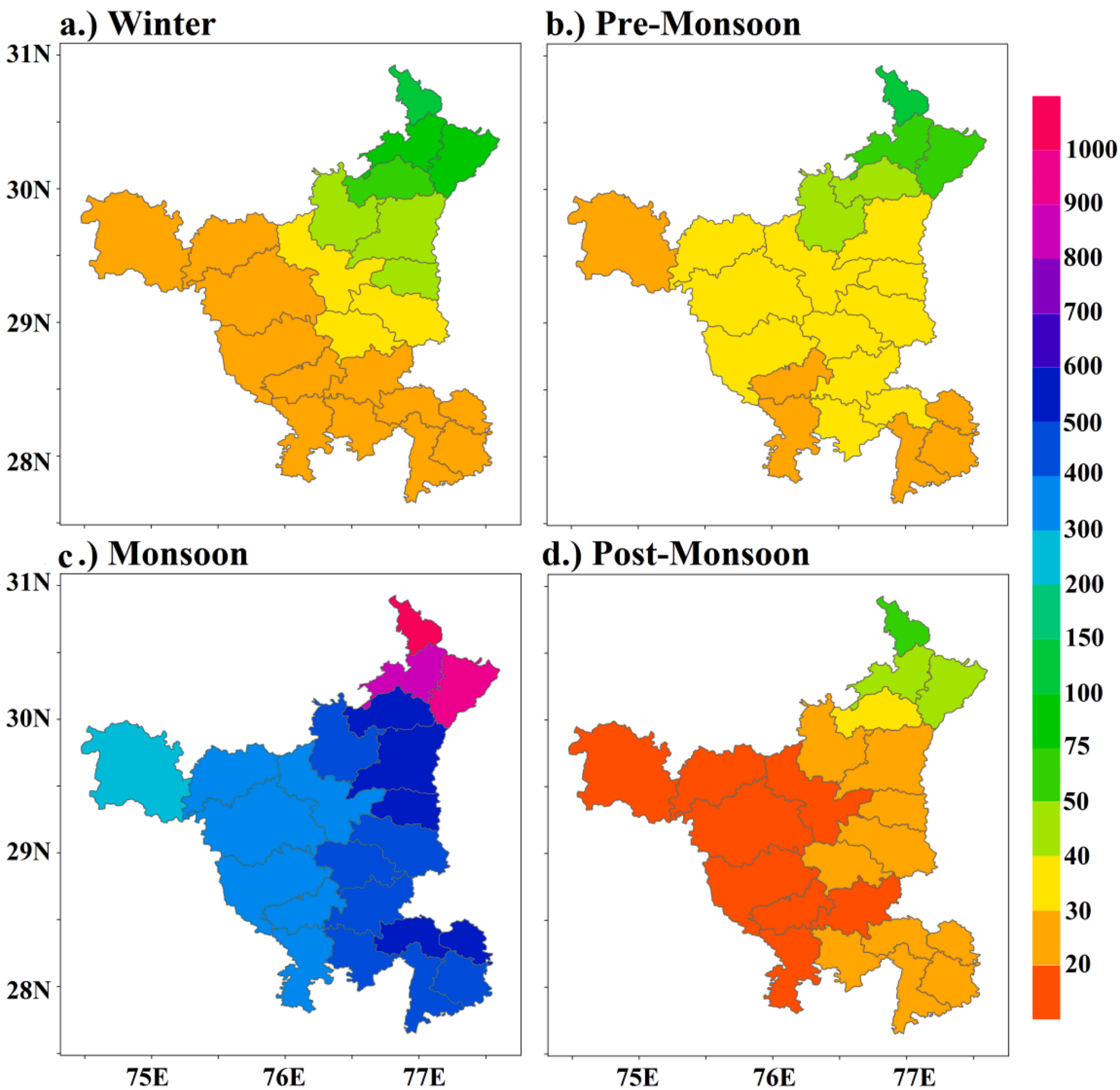

Fig. 3. The long-term distribution of mean precipitation (mm per season) observed during (a) winter season (b) pre-monsoon season, (c) monsoon season and (d) post-monsoon season for a period of 120 years (1901-2020) in the districts of Haryana state of India.

2.6 – 16.8%, and 0.2 – 4.8% of the rainfall events during the winter season in different districts of Haryana, respectivelyy. During the pre-monsoon season, the range of light, moderate and heavy intensity rainfall events for different districts in Haryana varied from 87.8 – 97.4%, 2.5 – 9.8%, and 0.1 – 2.3%, respectivelyy. The range of light, moderate and heavy intensity rainfall events in different districts of Haryana during the monsoon season varied from 69.6 – 88.9%, 8.7 – 18.6%, and 2.1 – 11.8%, respectivelyy. During the post-monsoon season, the range of light, moderate and heavy intensity rainfall events for different districts in Haryana varied from 80.7 – 95.9%, 2.7 – 13.1%, and 0.7 – 6.25%, respectivelyy. It was observed that the proportion of rainfall events having lesser RI was higher as compared to the ones having greater RI during each season at the districts level and vice-versa.

4.5. Deviation in different rainfall intensity categories

Percent deviation in light, moderate and heavy rainfall intensity (RI) events in different QDTs against the long-term mean of rainfall events in that specific intensity category of 120 years (RI120) from 1901 to 2020 during the different seasons at the district level was worked out for studying spatio-temporal variation in different RI categories. Positive deviation depicts the increase in number of rainfall events, while negative deviation depicts a decline in number of rainfall events in that specific RI category. Fig. 8 portrays the visuals of spatio-temporal variation of percent deviation in light rainfall intensity event (PDL) during different seasons at the district level in different QDTs against LPA120. A negative value of PDL was observed in 16 (72.7%) out of 22 districts during winter and 17 (77.3%) districts during the post-monsoon season in QDT3, which is suggestive of decreasing number of light rainfall events in most parts of Haryana during winter and post-monsoon season in last QDT. PDL during monsoon season showed a mixed behaviour with 9 (41.0%) districts showing negative while 13 (59.0%) districts showing positive values in the last QDT. However, all (100%) of the districts have shown positive PDL, which is indicative of an increase in the number of light rainfall events during the pre-monsoon season during QDT3 in Haryana. The spatio-temporal variation of percent deviation in moderate-intensity rainfall events (PDM) during different seasons at the district level in different QDTs against LPA120 can be seen

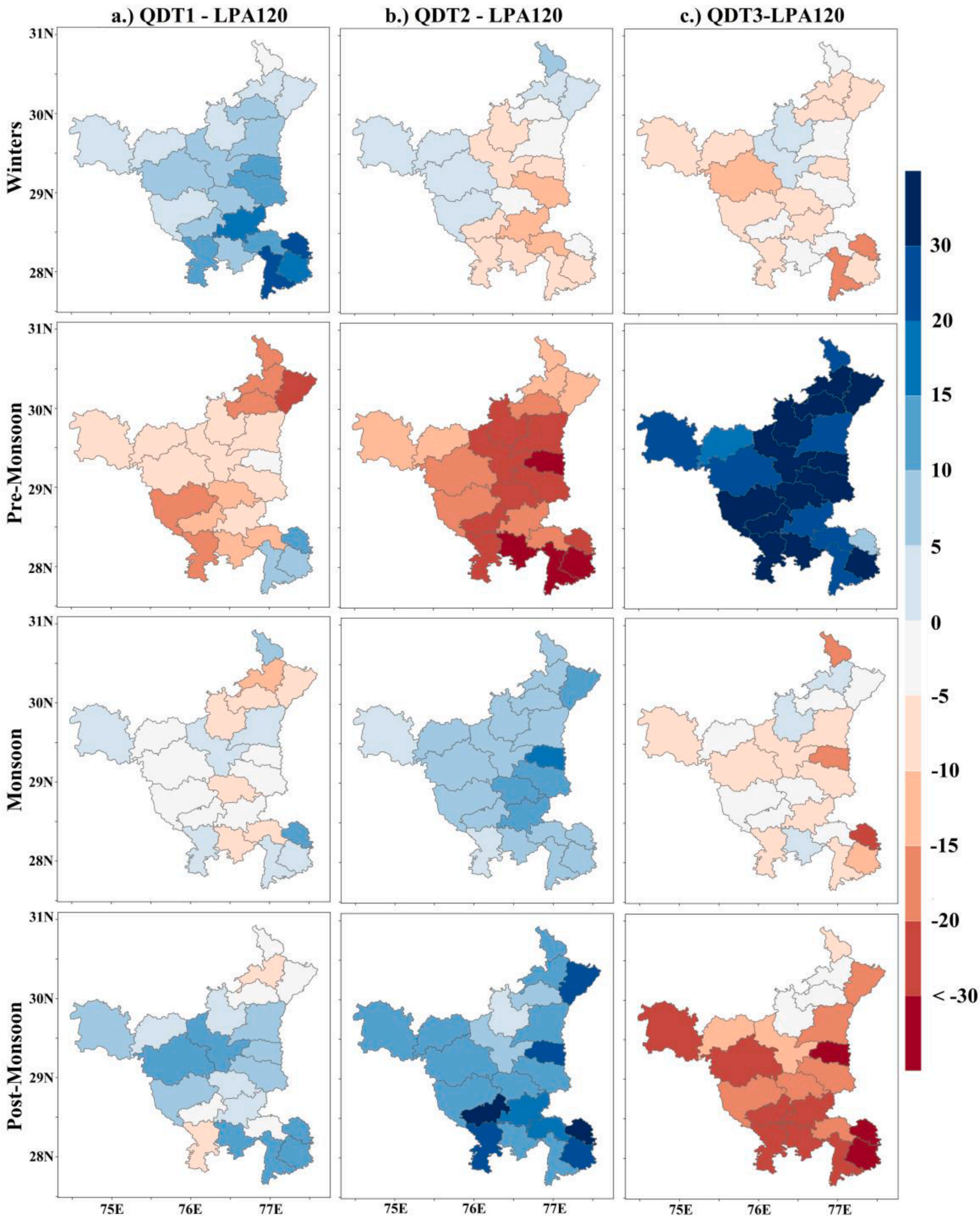

Fig. 4. The long-term distribution of per cent deviation of rainfall (%) presented in a.) QDT1, (b) QDT2, (c) QDT3 from long period average of 120 years (LPA120) observed during winter season (JF; 1st row), pre-monsoon season (MAM; 2nd row), monsoon season (JJAS; 3rd row) and post-monsoon season (OND; 4th row) in the districts of Haryana state of India.

from Fig. 9. A negative value of PDM was observed in 18 (81.8%), 16 (72.7%), and 17 (77.3%) out of 22 districts during winter, monsoon and post-monsoon season during QDT3, which is suggestive of declining number of moderate intensity rainfall events in most parts of Haryana during winter, monsoon and post-monsoon season in last QDT, respectivelyy. However, positive value of PDM was observed in 21 (95.5%) out of 22 districts, which is suggestive of rising number of moderate rainfall events in the pre-monsoon season during QDT3 in most parts of Haryana. The spatio-temporal variation of percent deviation in heavy intensity rainfall events (PDH) at the district level in different QDTs against LPA120 for different seasons can be perceived from Fig. 10. Mixed patterns of rise and fall in heavy rainfall events were observed during winter and pre-monsoon season, but a decrease in heavy intensity rainfall events was prevalent in monsoon and post-monsoon

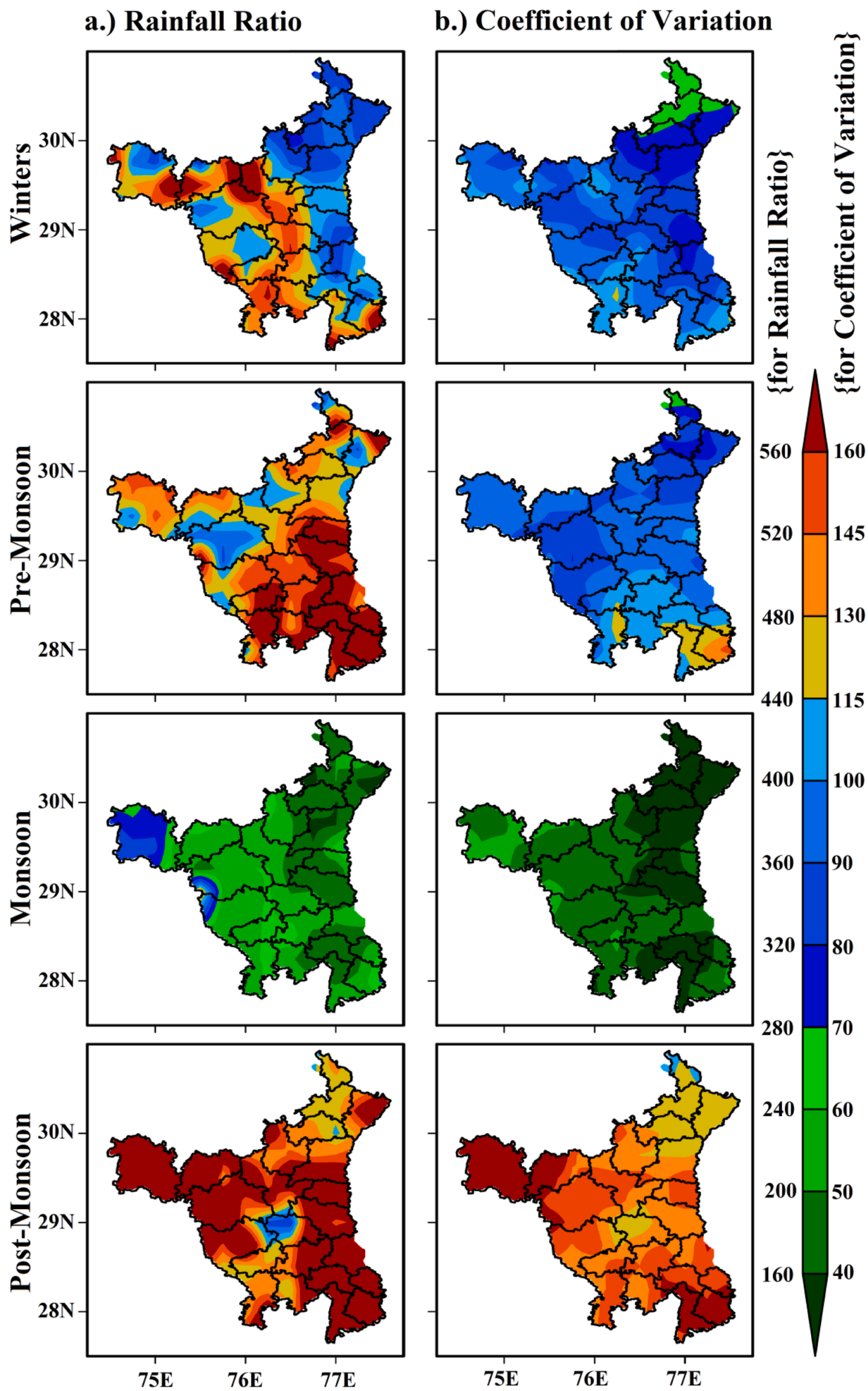

Fig. 5. The long-term distribution of (a) rainfall ratio (%) and (b) coefficient of variation (%) observed during winter season (JF; 1st row), pre-monsoon season (MAM; 2nd row), monsoon season (JJAS; 3rd row) and post-monsoon season (OND; 4th row) for a period of 120 years (1901-2020) in the districts of Haryana state of India.

season in most of the districts of Haryana during QDT3. Overall the magnitude of percent deviation in different rainfall intensity category events in different QDTs against the long-term mean of rainfall events was highest for heavy, followed by moderate and light intensity rainfall events.

4.6. *Trends of rain days*

The innovative trend analysis method (ITAM) as proposed by Şen (2017) was applied to the time series of rain days in different categories viz. light, moderate, and heavy rainfall based on the daily rainfall

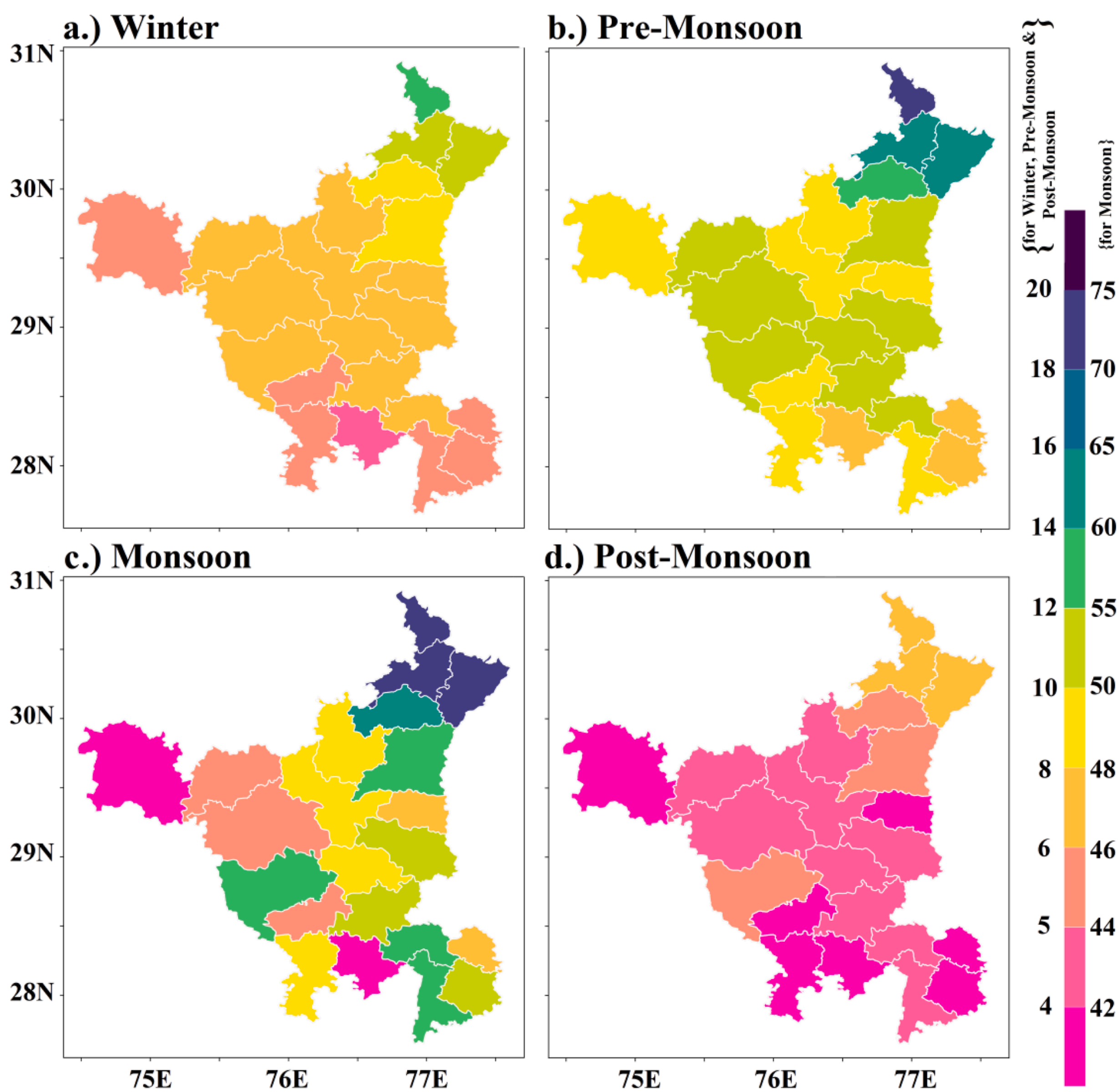

Fig. 6. The long-term distribution of mean number of rain days (rainfall ≥ 0.1 mm per day) observed during (a) winter season, (b) pre-monsoon season, (c) monsoon season and (d) post-monsoon season for a period of 120 years (1901-2020) in the districts of Haryana state of India.

intensity. The innovative trend indicator (ITI) was worked out for the time series of different rainfall intensity categories for each season at the district level for a period from 1901 to 2020. A positive value of ITI indicates an increasing trend and vice-versa. The results thus obtained for each season at the district level are presented in Fig. 11.

During the winter season, a significantly decreasing trend in light intensity rainfall events was observed at 14 (63.6%), whereas a significantly increasing trend was observed at 6 (27.2%) out of 22 districts of Haryana at a 99% confidence level. 19 (86.3%) districts have registered a significantly decreasing trend at a 99% confidence level whereas Rohtak registered a significantly decreasing trend at a 95% confidence level in moderate intensity rainfall events during the winter season. 4 (18.2%) and 1 (4.5%) out of 22 districts have registered a significantly decreasing and increasing trend at 99% confidence level, respectivelyy, whereas 3 districts showed significantly increasing trend at 95% confidence level in heavy intensity rainfall events during the winter season. Overall, most of the districts have shown a significantly decreasing trend in light and moderate rainfall intensity events, which is suggestive of a decrease in the frequency of rainfall under these categories during the winter season. This decreasing trend in the number of rain days during the winter season can be attributed to the decrease in western disturbances (WD). Kumar et al. (2015) observed a statistically significant (confidence level > 95%) decreasing trend in the frequency of WDs over northwest India. A decrease in frequencies of WD is also reported by Cannon et al. (2016), Hunt et al. (2018), Zaz et al. (2019), and Midhuna et al. (2020). Kumar et al. (2010) also conducted a trend analysis of the number of rainy days for three stations of Kashmir valley for the period 1903 to 1982 and found a statistically significant decrease trend at the 95% confidence level. Suryavanshi et al. (2014) carried out a trend analysis of the number of rainy days for a period of 31 years from 1973 to 2003 and found 14 stations with a significant decreasing trend in the number of rainy days at Bhopal, Hamirpur, Shivpuri, and Tikamgarh during the winter season.

During the pre-monsoon season, 21 (95.5%) out of 22 districts of Haryana witnessed a significantly increasing trend in light intensity rainfall events at a 99% confidence level. 20 (90.9%) districts have registered a significantly increasing trend at 99% confidence level whereas Faridabad and Palwal registered a significantly decreasing

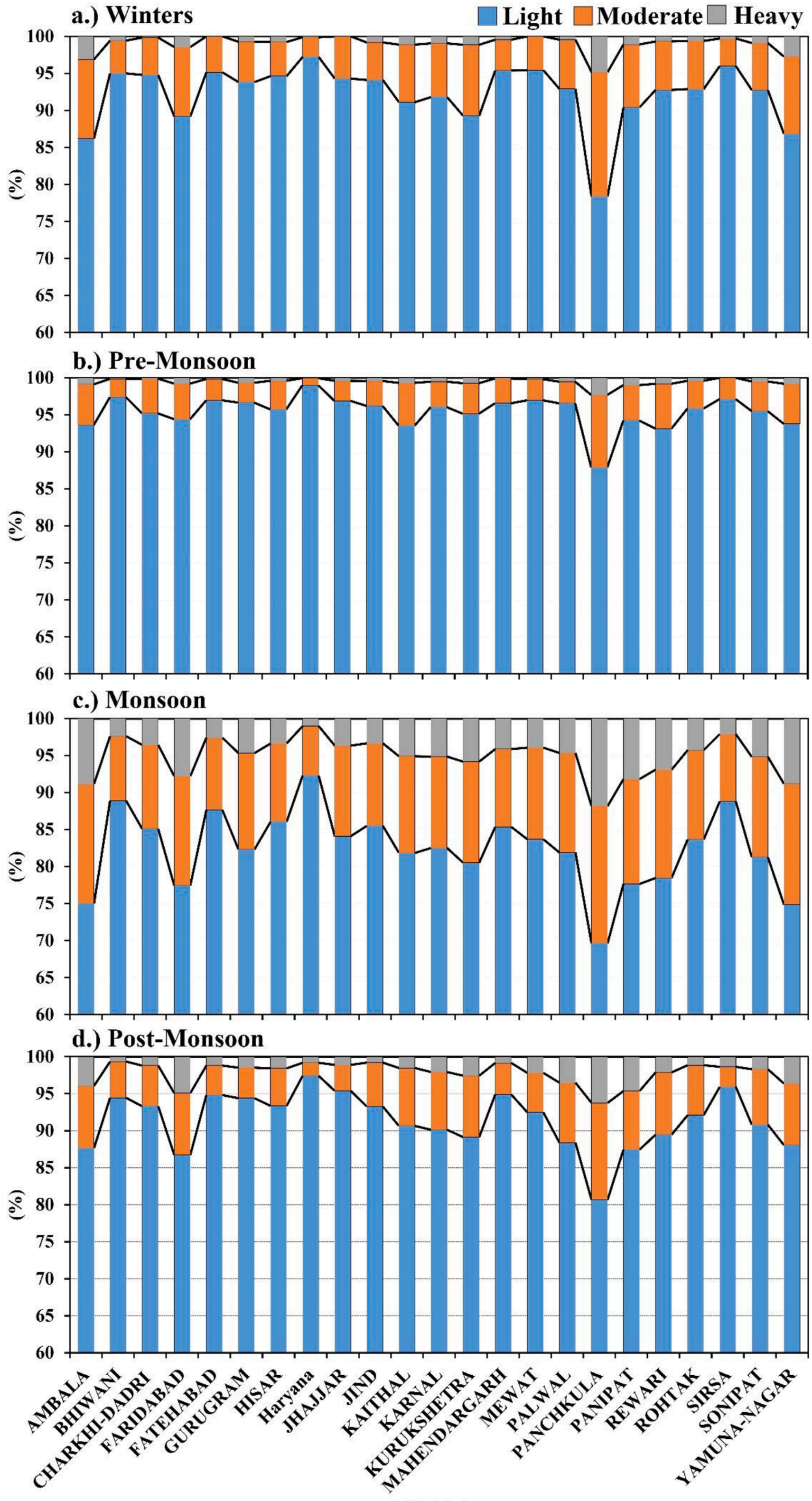

Fig. 7. The long-term distribution of light (0.1 to 15.5 mm), moderate (15.6 to 35.5 mm), and heavy (35.6 mm and above) rainfall events expressed as a percentage of the mean number of rain days in stacked chart columns as per the classification of India Meteorological Department observed during (a) winter season (b) pre-monsoon season, (c) monsoon season and d.) post-monsoon season for a period of 120 years (1901-2020) in the districts of Haryana state of India.

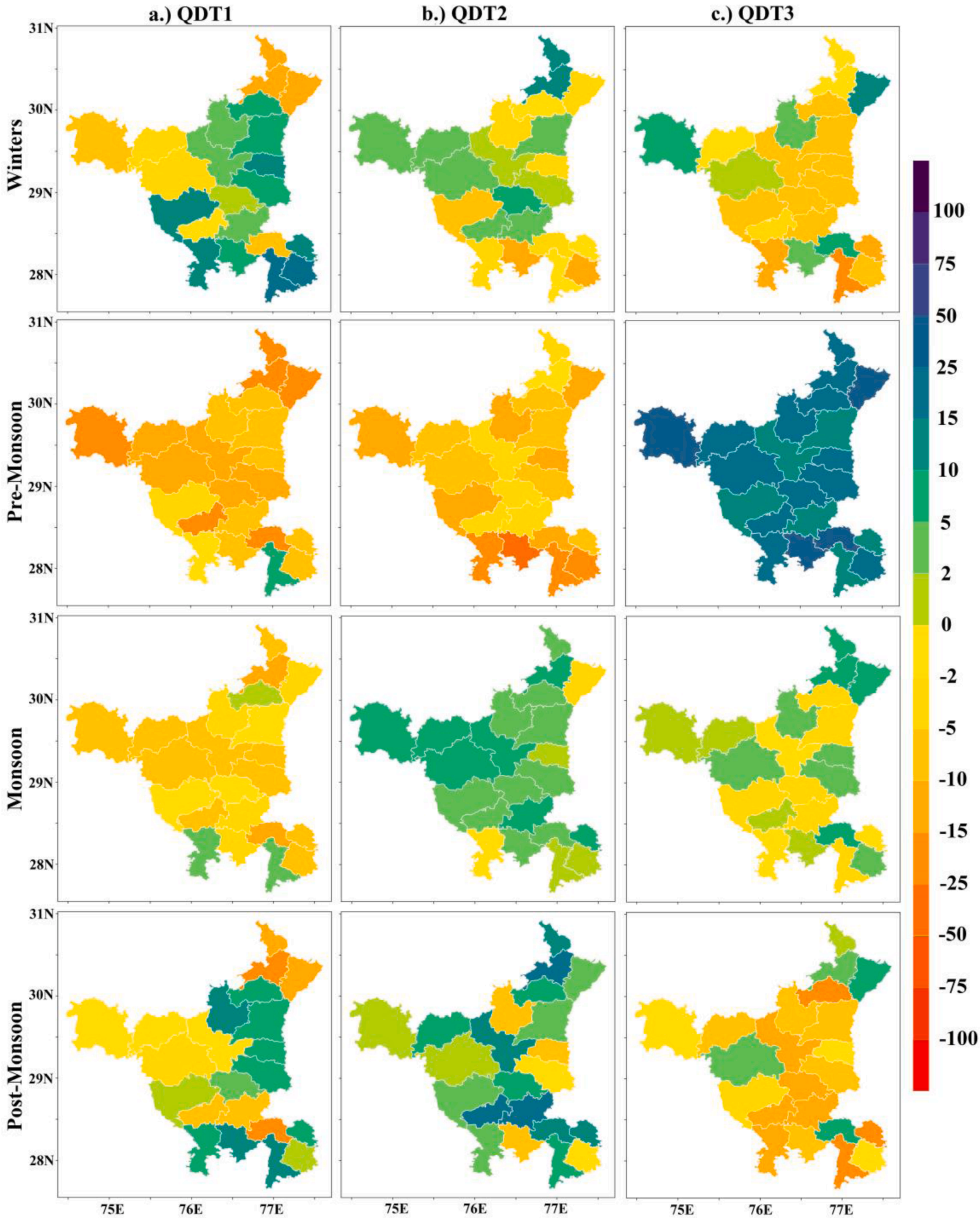

Fig. 8. The long-term distribution of percent deviation in the intensity of light (0.1 to 15.5 mm) rainfall events (%) presented in (a) QDT1, (b) QDT2, (c) QDT3 against the long-term mean of light rainfall events observed during winter season (JF; 1st row), pre-monsoon season (MAM; 2nd row), monsoon season (JJAS; 3rd row) and post-monsoon season (OND; 4th row) for a period of 120 years (1901 to 2020) in the districts of Haryana state of India.

trend at 99 and 95% confidence levels in moderate intensity rainfall events during pre-monsoon season, respectivelyy. Only 3 (13.6%) districts perceived a statistically significant decreasing, whereas 5 (22.7%) out of 22 districts of Haryana observed a significantly increasing trend in heavy intensity rainfall events at either 99% or 95% confidence level during the pre-monsoon season, respectivelyy. Overall, most of the districts have shown a significantly increasing trend, which is suggestive of an increase in the frequency of rainfall under light and moderate rainfall intensity categories during the pre-monsoon season. Choudhury et al. (2012) observed an increasing trend during pre-monsoon rain days in mid-altitude Meghalaya of North-East India for 27 years from 1983 to 2010.

Vinay Kumar et al. (2020) also observed an increase in the frequency of the number of rainy days during the active pre-monsoon season over

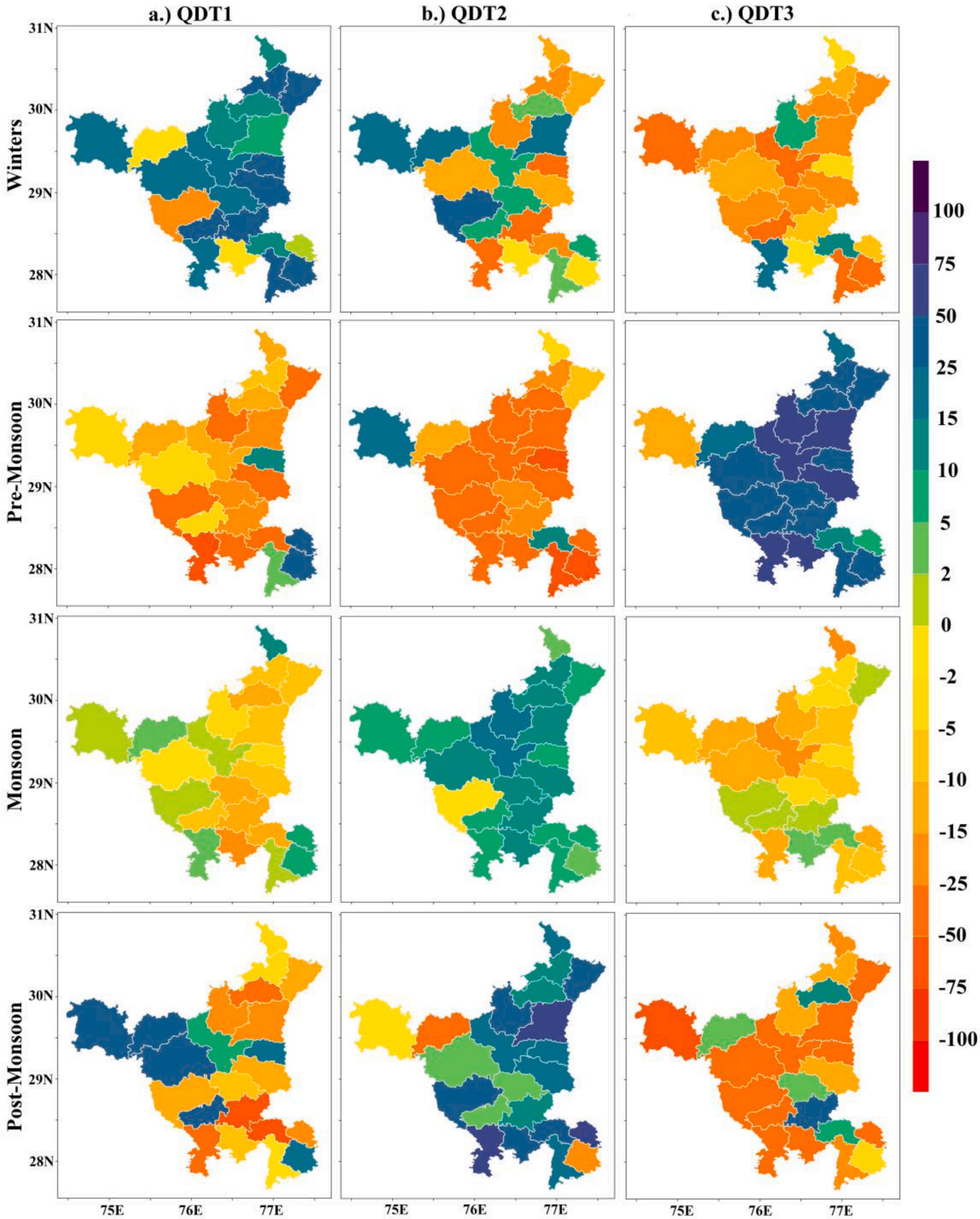

Fig. 9. The long-term distribution of per cent deviation in the intensity of moderate (15.6 to 35.5 mm) rainfall events (%) presented in (a) QDT1, (b) QDT2, (c) QDT3 against the long-term mean of moderate rainfall events observed during winter season (JF; 1st row), pre-monsoon season (MAM; 2nd row), monsoon season (JJAS; 3rd row) and post-monsoon season (OND; 4th row) for a period of 120 years (1901 to 2020) in the districts of Haryana state of India.

different parts of India. Umakanth et al. (2022) also noticed an increasing trend in pre-monsoon rain days over four stations of Kerala, India.

During monsoon season, a significantly decreasing trend in light intensity rainfall events was observed at 4 (18.8%), whereas a significantly increasing trend was observed at 17 (77.3%) out of 22 districts of Haryana at a 99% confidence level. Moderate intensity rainfall events were observed by 10 (45.5%) out of 22 districts for each significantly increasing as well as decreasing trends during monsoon season. 14 (63.6%) districts have registered a significantly increasing trend at a 99% confidence level whereas 8 (36.4%) out of 22 districts encountered a significantly decreasing trend at a 99% confidence level in heavy intensity rainfall events during monsoon season, respectivelyy. Overall, the monsoon season has shown dichotomic behaviour, with some

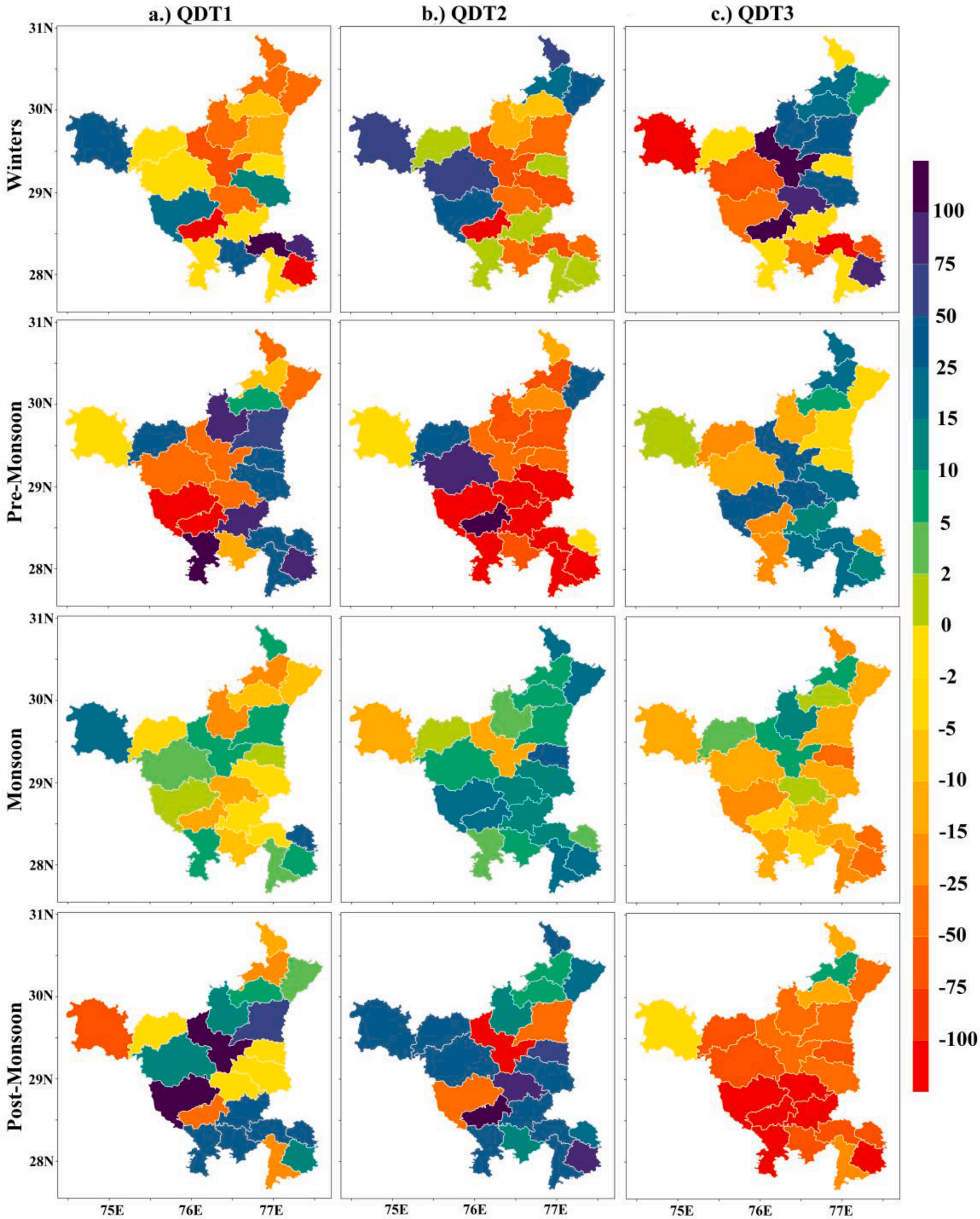

Fig. 10. The long-term distribution of per cent deviation in the intensity of heavy (35.6 mm and above) rainfall events (%) presented in (a) QDT1, (b) QDT2, (c) QDT3 against the long-term mean of heavy rainfall events observed during winter season (JF; 1st row), pre-monsoon season (MAM; 2nd row), monsoon season (JJAS; 3rd row) and post-monsoon season (OND; 4th row) for a period of 120 years (1901 to 2020) in the districts of Haryana state of India.

districts showing rising while others showing a falling trend in moderate intensity rainfall. However, an increasing trend was observed in both light and heavy rainfall intensity categories in more than 60% of the districts. Dash et al. (2009) analyzed the number of rainy days for a period of 53 years from 1951 to 2004 and found that the number of moderate rain days averaged over the whole country has decreased significantly during the monsoon season. A similar significant reduction was observed in the number of low rain days, while, the number of heavy rain days considered over entire India shows some indications of increase, but the trend was not statistically significant. Das et al. (2014) also observed a significant decreasing trend in the number of rainy days during monsoon over the north and central region of India covering Punjab, Haryana, west and east Uttar Pradesh, west and east Madhya Pradesh, Gujarat, and Orissa. Our findings are also in conformity with

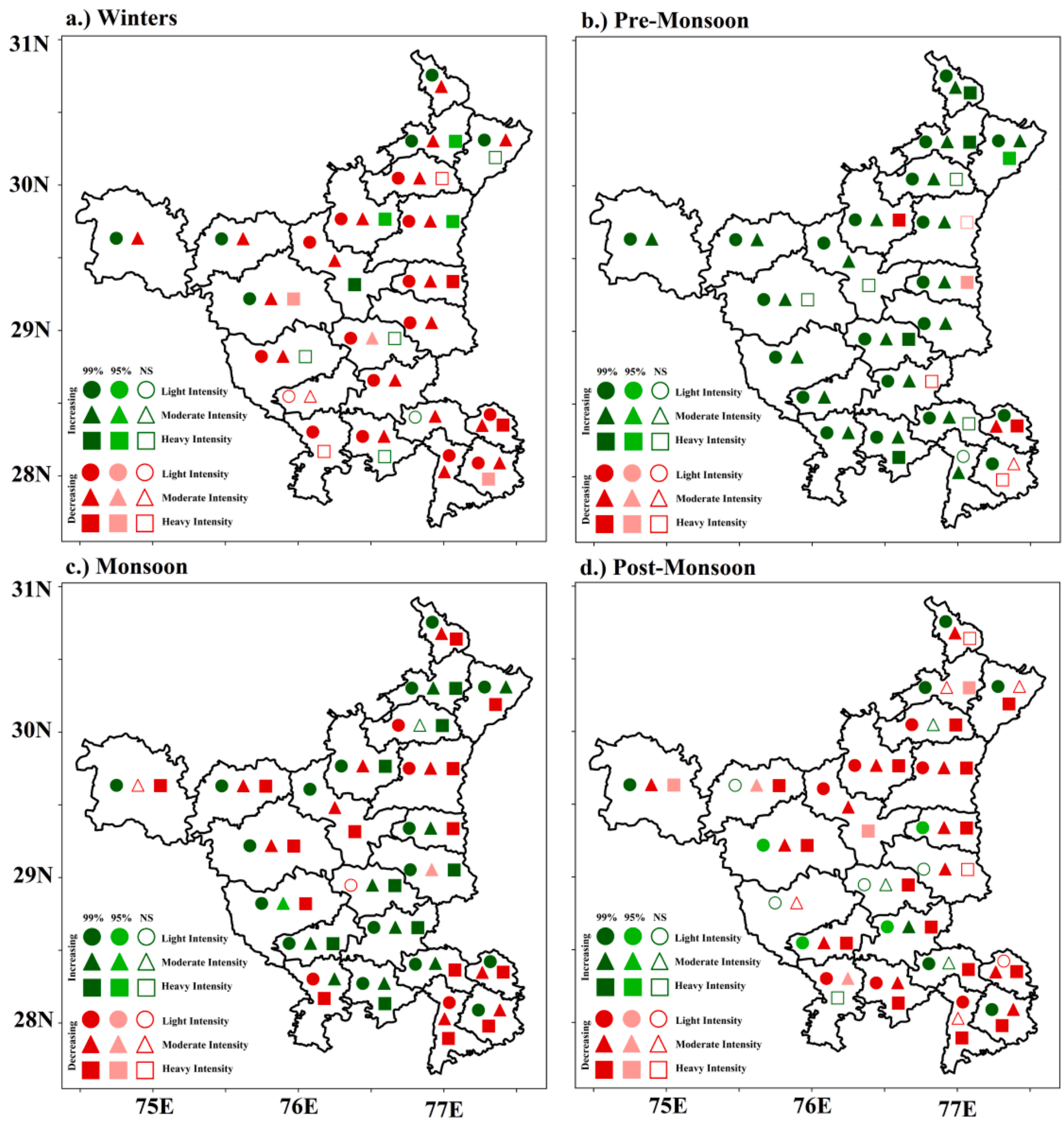

Fig. 11. The trends of light (0.1 to 15.5 mm), moderate (15.6 to 35.5 mm), and heavy (35.6 mm and above) rainfall intensity events as per innovative trend analysis method (ITAM) during (a) winter season, (b) pre-monsoon season, (c) monsoon season and (d) post-monsoon season in the districts of Haryana state of India. The significance of trend was tested at 95% and 99% confidence level. The green and red colours are indicative of increasing and decreasing trends, respectivelyy. The light colour of solid symbols depicts that trend is significant at 95% confidence level, while dark colour indicates significance at 99% confidence level. The hollow symbols are indicative of non-significant trends, while the districts in which symbol for specific category is absent depicts that no trend was observed in rainfall in that specific category.

the results of Guhathakurta et al. (2015) who observed the frequency of rainfall in different categories during the monsoon season. They found that the frequencies of rain days (if rainfall of the day is $\geq$ 0.1 mm) have decreased in most parts of the country except some regions of west peninsular India, viz. Madhya Maharashtra, north and south interior Karnataka and Lakshadweep, whereas an increasing trend in the frequency of heavy rainfall events dominated during the period 1901–2011 in 17 out of 36 subdivisions, including Haryana, Delhi & Chandigarh and Punjab.

During the post-monsoon season, 7 (31.8%) out of 22 districts of Haryana witnessed a significantly decreasing trend at a 99% confidence level, whereas 10 (45.5%) out of 22 districts registered a significantly increasing trend at either 99 or 95% confidence level in light intensity rainfall category during post-monsoon season, respectivelyy. 14 (63.6%) out of 22 districts have registered a significantly decreasing at either 99% or 95% confidence level, whereas Jhajjar was the only district to show a statistically significant increasing trend at 99% confidence level in moderate intensity rainfall events during post-monsoon season. 18 (81.8%) out of 22 districts have registered a significantly decreasing at either 99% or 95% confidence level, whereas no district encountered a statistically significant increasing trend in heavy intensity rainfall events during the post-monsoon season. Jhajharia et al. (2012) also investigated the trends in the number of rainy days using the Mann-Kendall non-parametric test at 24 stations, out of which 6 stations witnessed statistically significant decreasing trends in the number of rainy days during post-monsoon seasons at a 5% level of significance.

4.7. Dominant EOF patterns of Rainfall variability

There is a large spatial variability in rainfall during different seasons (Rasmusson and Carpenter, 1983; Pant and Rupa Kumar, 1997). The seasonal rainfall is highly correlated between some adjacent subdivisions in the northwest, central, and peninsular India (Parthasarathy, 1984) so it was necessary to perform an empirical orthogonal function (EOF) analysis of the seasonal rainfall to have a better idea about the spatial distribution of rainfall in Haryana during different seasons. As

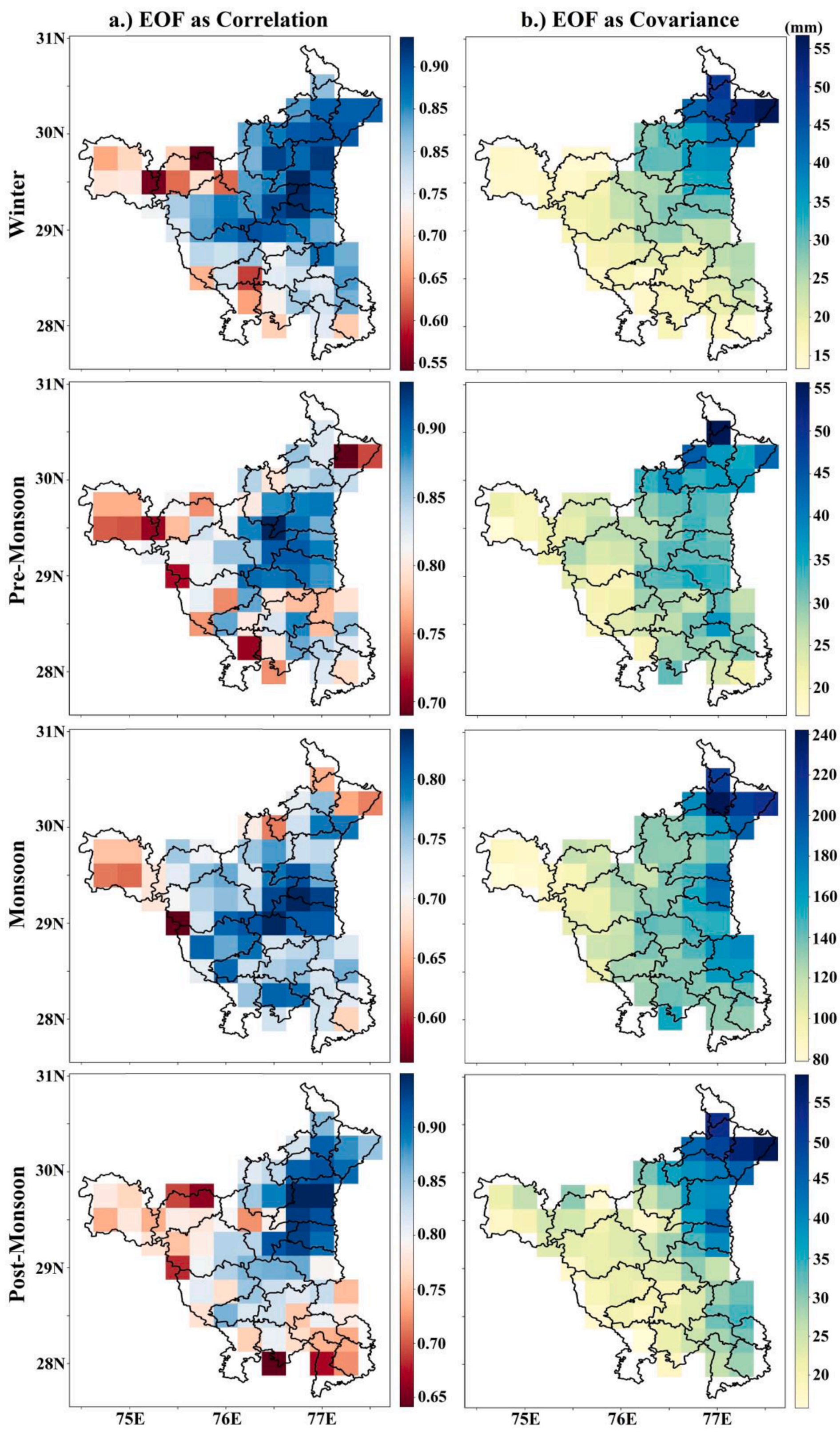

Fig. 12. The first dominant EOF loading (EOF1) for rainfall variability where, (a) EOF expressed as the correlation, and (b) EOF expressed as the covariance between the principal component time series (PC) and the time series of the EOF input dataset at each grid point, observed during winter season (JF; 1st row), pre-monsoon season (MAM; 2nd row), monsoon season (JJAS; 3rd row) and post-monsoon season (OND; 4th row) for a period of 120 years (1901 to 2020) in the districts of Haryana state of India.

described in the "Methodology" section, one dominant EOF (EOF1) for each season based on the value of the eigenvector carrying maximum variance was considered in this study, and it was estimated in two ways: (a.) EOF expressed as the correlation between the principal component time series (PC) and the time series of the EOF input dataset at each grid point shown in Fig. 12a, and (b.) EOF expressed as the covariance between the PC time series and the time series of the EOF input dataset at each grid point shown in Fig. 12b. EOF1 explained 69.1%, 67.8%, 53.9%, and 70.3% of the total variability during winter, pre-monsoon, monsoon, and post-monsoon season over the study region which is suggestive of the most stable rainfall and most variable rainfall patterns during monsoon and post-monsoon season, respectivelyy. The higher values of EOF as correlation during almost all seasons were observed in the eastern part of Haryana as compared to the western counterpart of the study area, which indicates that the variability of rainfall was higher in the districts lying in western Haryana while more stable rainfall was observed in the districts lying in the eastern part of Haryana. The higher values of EOF as covariance in the eastern part as compared to the western part of Haryana during each season can be attributed to the higher value of mean seasonal rainfall received by the districts lying in the eastern part of Haryana and vice-versa. Results observed during EOF analysis for the different seasons are in conformity with the ones observed in coefficient of variation (CV) and seasonal rainfall ratio (SRR) analysis in Section 4.3 described above.

The corresponding principal components (PCs) of each EOF1 observed during different seasons are shown in Fig. 13, with normalised PC scores. The PC clearly shows that entire state has experienced epochal fluctuations during the entire investigation span. The years extracted by PC having normalised PC scores below zero can be termed as years with deficient while the ones having normalised PC scores above zero can be termed as years with excess precipitation. During the winter season, the years 1942, 1954, and 1961 were the years from QDT2 and 2013 was the year from QDT3 with normalised PC score of less than -2 indicative of extreme deficient rainfall during these years. During the pre-monsoon season, year 1913 from QDT1, and the year 1982, 1983, 2008, 2015, 2020 were from QDT3 with a normalised PC score of more than 2, indicative of excess rainfall during these years. During the monsoon season, 1987 was the only year having normalized anomaly of less than -2, whereas 1917 and 1933 from QDT1, 1942 and 1964 from QDT2, 1988 and 1995 from QDT3 were the years with normalized anomaly of more than 2. During the post-monsoon season 1910 and 1917 from QDT1, 1955 and 1956 from QDT2, 1997 and 1998 from QDT3 were the years with a positive normalized anomaly of more than 2 which can be termed as excess rainfall years during the post-monsoon season. The years extracted by PC analysis also match with the results obtained during the analysis of DRP during different seasons at the district level in different QDTs against LPA120.

5. Conclusions

In the present study, the dynamics of seasonal rainfall time series data of 120 years (1901–2020) for 22 districts of Haryana, India, were analysed using spatio-temporal patterns of mean rainfall, rainfall deviation, seasonal rainfall ratio (SRR), coefficient of variation (CV), number of rain days, rainfall intensity and trends of rain days, Empirical Orthogonal Functions (EOF) and Principal Component (PC) analysis. The districts lying in the eastern Haryana had received higher rainfall in each season than the ones lying in its western counterpart. Rainfall during pre-monsoon season has shown positive rainfall deviation, while it was negative for all the other seasons during the QDT3 which is indicative of decreasing rainfall at most of the districts of Haryana during winter, monsoon and post-monsoon season in recent times. The higher variability in rainfall was observed over the districts lying in western Haryana as compared to the ones lying in eastern Haryana during all seasons. Among different seasons, monsoon season had received maximum rain days, followed by pre-monsoon, winter, and post-monsoon season in Haryana. The number of rain days has decreased during the winter and post-monsoon seasons, while increased during the pre-monsoon season in most of the districts of Haryana as per the innovative trend analysis method (ITAM). In most districts, the

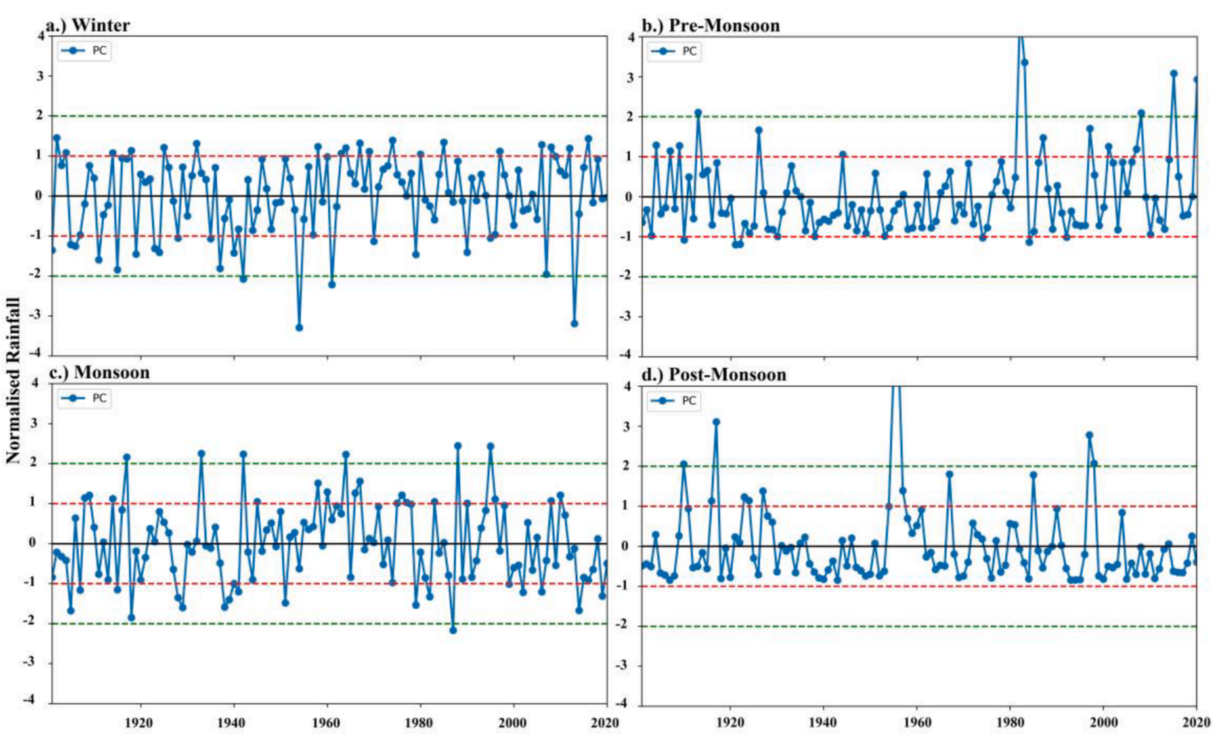

Fig. 13. The time series of normalised anomaly of seasonal rainfall for corresponding principal component (PC) of the dominant EOF (EOF1) observed during (a) winter season, (b) pre-monsoon season, (c) monsoon season and (d) post-monsoon season for a period of 120 years (1901-2020) in the Haryana state of India.

monsoon season has exhibited a declining trend in moderate intensity whereas increasing trend in both light and heavy rainfall intensity category rainfall events. The presence of these trends depicts the impact of climate change and climatic variability on rainfall and number of rain days. The maximum variability was described by dominant EOF analysis during the post-monsoon season, followed by winter, pre-monsoon, and monsoon seasons. Inter-annual variability in rainfall during each season was also detected by PC analysis. Our findings have assessed the descriptive and analytical features of rainfall patterns for seasonal rainfall in different districts of Haryana. Such analysis along with the spatio-temporal maps would be useful for planning well-organized use of water resources and also for district-level water management in a sustainable manner considering the impact of climate change on changing rainfall pattern and number of rain days in a particular season in Haryana. The agricultural or other socio-economic activities can also be managed by taking into account the changing rainfall pattern discussed in this paper.

Declarations

Data availability

The daily gridded rainfall data for conducting this study is openly available at https://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html.

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Ethics approval

The authors declare that they have no conflict of interest.

Consent to participate

Not applicable

Consent for publication

All authors give the consent for the publication of identifiable details, which include figures within the text to be published in this manuscript.

CRediT authorship contribution statement

Abhilash Singh Chauhan: Methodology, Investigation, Data curation, Methodology, Writing – original draft. **Surender Singh:** Conceptualization, Methodology, Visualization, Writing – review & editing. **Rajesh Kumar Singh Maurya:** Data curation, Conceptualization, Methodology, Visualization, Writing – review & editing. **Alka Rani:** Conceptualization, Methodology, Visualization, Writing – review & editing. **Abhishek Danodia:** Conceptualization, Methodology, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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