



# The anatomy of extreme precipitation events over Srinagar, Kashmir, India, over the past 50 years

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## Abstract

Extreme precipitation is considered one of the deadliest events causing climatological catastrophes around the globe. With the upsurge in global temperature, the chances of unprecedented events are increasing, continually escalating implications on society. The paper's native aim is to understand the spatial-temporal variability of extreme precipitation indices connected with global oscillations over Srinagar city in central Kashmir, India. For the quantification of extreme precipitation, three types of precipitation indices based on percentile threshold and six types of fixed threshold indices have been utilized over the study region. Trend analysis has been performed on these extreme precipitation indices along with the Lag correlation technique to see the interference of these events with three global oscillation indices (El Niño southern oscillation (ENSO), Pacific decadal oscillation (PDO), and Atlantic multidecadal oscillation (AMO)). The observations depicted that the daily precipitation over the study region falls in the range of 5 to 30 mm, with 50-mm precipitation to be considered unprecedented as it shows maximum correlations with the discharge. Hence, precipitation of such intensity can cause flood situations in the study area. On observing the trend in these extreme precipitation indices, it is found that a slightly increasing trend exists in all extreme precipitation indices, with consecutive dry days showing a decreasing trend. The ENSO and PDO are positively correlated with all extreme precipitation indices in zero-lag primarily, while AMO only affects R<sub>30–50</sub> in a positive way. This study can be helpful for the flood forecasting system and assist in managing the water resources system, as it has quantified the precipitation excess and deficit years.

**Keywords** Trend analysis · Extreme rainfall indices · ENSO · AMO · PDO

## Introduction

Global warming has modified the weather patterns by bringing unprecedented extreme events at both global and regional scales. According to the IPCC 2007 report, the global average air temperature has increased by 0.74° C during the last centennial, leading to the urge of understanding extreme weather events with warming. The weather extremes like floods, droughts, and intense heatwaves are considered deadly events that are affecting globally with different perspectives. The variability of these extremes is still unclear as wet regions are getting wetter and dry regions are getting drier (Hill et al., 2018), confirming the

modification of the global hydrological cycle, which in turn creates water security in the drought-prone region around the globe. Hence, understanding the spatial-temporal variability of precipitation and its extremes will help to manage the future water resources over an area.

The Himalayas form the potential natural water resource to the major river systems of the Indian regions, so the variability of discharge with precipitation in monsoon and non-monsoon seasons is a primary concern to study the deficit and rainfall excess years and governing factors controlling this variability. The spatial-temporal variability of rainfall and its extremes over Northwest Himalayas and its internal regions has been well documented, as one of the studies (Gujree et al., 2017) pointed towards the spatial variability of temperature and precipitation extremes over the Kashmir valley using the RCLIMDEX model and pinned down that plain areas exhibit an increasing trend in maximum temperature extremes, while the frequency of extreme precipitation and minimum temperature events follow an increasing trend at higher altitudes depicting that smaller area are also prone to variability in extremes.

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Srinagar city, the central portion of the Kashmir valley, has a history of great floods and is considered the most vulnerable area to floods. Ahmad et al. (2016) pointed towards the vulnerability of this region to flood hazards and classified Srinagar into three main vulnerable zones, i.e., highly vulnerable, moderately vulnerable, and least vulnerable, with 20% of the total population occupied by highly vulnerable zone, whereas the rest are moderately and least vulnerable to flood hazards. A total of 80% of residential houses were partially submerged, while 20% were completely washed due to the floods of 2014 (Gulzar et al., 2020).

Since climate change is on the verge of drawing its footprints over this region, as revealed by Qadri and Dar (2020), the patterns of precipitation and temperature over the Srinagar region have been modified with an increase/decrease of annual average temperature and precipitation by 0.6° C and 6.1 mm up to 2031. Hence, the variability of precipitation and temperature is most important concerning the living population and agriculture over this region. The modification in precipitation patterns at different scales increases the vulnerability of a region to natural calamities. To decrease the potential impacts of climate variability, the analysis and forecast system of various rainfall extremes with global oscillations is the need of the hour. Meraj et al. (2018) worked on flood forecasting over the Jhelum basin using HEC\_GeoHMS hydrological model and found a high correlation between the observed and simulated discharge, confirming that the model performed well from August to September, which is probably seen as the vulnerable period for floods, as the 2014 flood occurred in September which led to devastation over the valley of Kashmir with Srinagar city as the epicenter.

The magnitude of a natural disaster like a flood or drought depends on the characteristic factors controlling the disaster, e.g., the governing factors are intensity and duration of precipitation in the case of floods. Hence, an extreme precipitation event leads to devastating floods on a global or local regional basis. To capture such events, a useful and homogeneous data set is required for analysis. Banerjee and Dimri (2019) studied extreme rainfall events via cloud bursts over one of the regions of Jammu and Kashmir (Ladakh). On comparison of data sets, they concluded that TRMM 3B42 and IMD rainfall captures the extreme events more clearly than other types of satellite datasets. As the climate becomes more variable, the chances of extremes to occur are more at a different temporal basis. Hence, the mechanism behind this modification is an important concern as it can lead to more devastating events in the oncoming future, as few studies have revealed the change of precipitation and temperature patterns over Jammu and Kashmir and its internal regions. Zaz et al. (2018) reported 0.8° C modifications in temperature over a 30-year period from 1980 to 2017, especially the variation in winter temperature and precipitation over this region is modulated by North Atlantic oscillations, and have studied that the 2014 extreme flooding over the Kashmir was due to breaking

of Rossby wave train which modulated the transport of moisture from Arabian seas and Bay of Bengal.

As the extreme precipitation events vary in space, time, and elevation over the Northwest Himalayas region, the quantification of extreme precipitation events becomes difficult as to whether to choose percentile or static method. Bharti (2015b) studied extreme rainfall over NWH by using the percentile method and determined that this region experiences a decrease in the characteristics of extreme rainfall events with elevation. On the other hand, Nandargi and Dhar (2012) pointed to the same region about the extreme precipitation and observed that there is an increase in the frequencies of extreme precipitation during two periods with a gap of 30 years, that is from 1951–1960 to 1991–2000 and a corresponding decrease in the frequencies from 2001 to 2007, leading to the confirmation of decadal variability of rainfall over the region. Hence, it can be revealed that the extreme precipitation varies both spatially and temporally over the entire northwest Himalayas. To get an idea about the possible outcomes of an increase in intensity and frequency of these extreme rainfall events over this region, regional studies become significant concerning the living population. Arora et al. (2016) have pointed towards the extreme precipitation over Kashmir in consideration with September 2014 flood and concluded that most of the meteorological stations had observed 156.7-mm daily rain leading to the overflow of river embankments and causing severe flooding leading to loss of life and infrastructure because of lack of flood forecasting in this region.

The variability of extreme precipitation in connection with global oscillations will help to understand the possible mechanism underlying these extremes, that is, floods and drought as few studies have pointed towards the relationship of Indian summer Monsoon rainfall with global oscillations like Atlantic multidecadal oscillation (AMO), Pacific decadal oscillation (PDO), and El Niño southern oscillation (ENSO). Naidu et al. (2020) suggested that Atlantic multidecadal AMO creates a differential in heating between Asia landmass and the Indian ocean, which in turn can control the variability of rainfall excess and deficit years. Also, PDO has affected the Indian summer Monsoon rainfall, as the warm (cold) phase of the PDO is related to the deficit (excess) rainfall and a corresponding increase (decrease) in the surface temperature over the Indian subcontinent (Krishnan and Sugi, 2003; Krishnamurthy and Krishnamurthy, 2014). Also, extreme precipitation variability can be related to sea surface temperature fluctuations in the Indian and Pacific oceans. Rajeevan et al. (2008) suggested that the frequency of extreme rainfall over India shows inter-annual to inter-decadal variations. It is controlled by the SST variability over the tropical Indian ocean. Also, an increase in SST over the Indian ocean has led to a greater risk of extreme rainfall and flooding over central India. Taking this insight into prime concern, the study is all about quantifying extreme precipitation using various fixed and percentile-based thresholds over the study region and correlating

these extreme events with three global oscillation indices (ENSO, PDO, and AMO) to check the interference in them.

### Study area

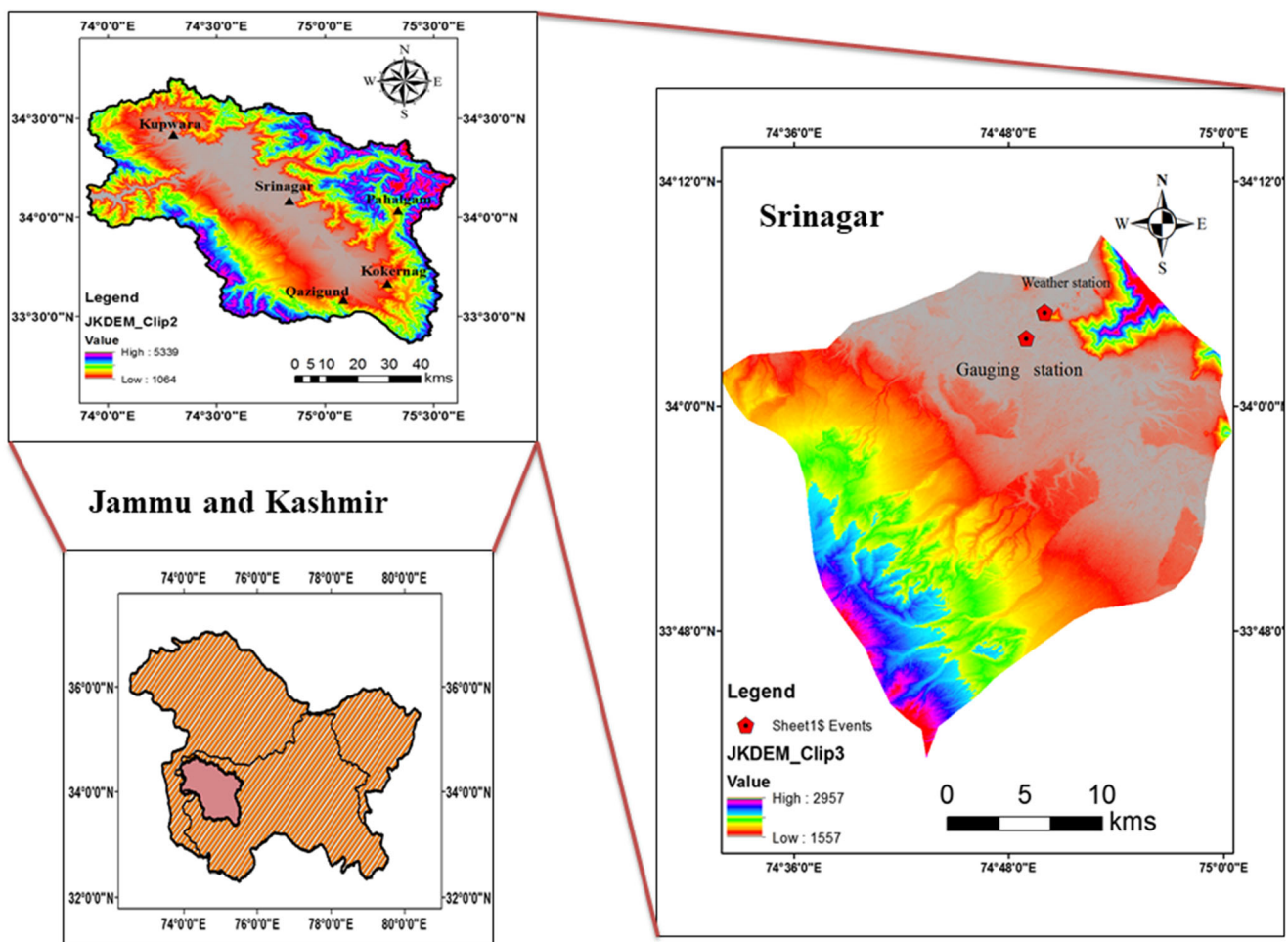
Srinagar is the attractive summer capital of Jammu and Kashmir situated to Northwest Himalayas between 74° 56' E–75°79'E longitude and 33° 18'N–34° 45' N latitude. The region experiences varying topographical features with a low elevation of 1557m and a high peak at 2957m, as revealed in Figure 1. Srinagar city forms a cup-like structure bounded by mountains throughout with beautiful Dal Lake and Mughal gardens on its shore, hence vulnerable to heavy tourism throughout the year. The Jhelum River meanders from the city moving onwards to north Kashmir divides the city into two drainage catchments connected by its nine historic bridges. The climate of Srinagar is generally subtropical, with varying temperatures and rainfall at different temporal scales. As reported by the Srinagar meteorological station, rainfall is in the range of 650–720 mm at an annual time scale (Qadri and Dar,

2020). The Srinagar city forms the hot spot for floods as torrential rainfall lashes the city and its upper basin, creating a huge loss of life and infrastructure, thus making the study region a primer concern for extreme rainfall studies.

### Data and methodology

#### Data

In this study, daily precipitation data for half a century, from 1969 to 2018, was collected from IMD Pune over the Srinagar station. The gauge data was obtained from the Irrigation and Flood Control (IFC) Department, Srinagar, for the same calibration period to see the relation of extreme precipitation with the discharge over the study region. Apart from this, the climate oscillation (AMO, PDO, and ENSO) index data has been obtained online from the physical science laboratory (<https://psl.noaa.gov/data/climateindices/list/>).



**Figure 1** Geographical setting of the study area Srinagar Jammu and Kashmir, India, showing the elevation in meters (m) from digit elevation map (DEM) with the locations of weather and Gauging station

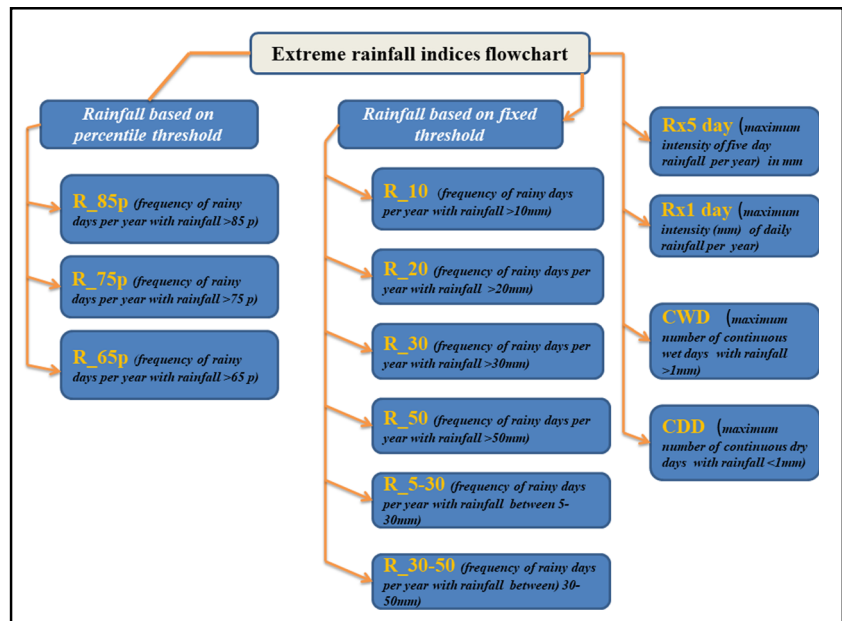
## Methodology

In this study, precipitation has been categorized using two main criteria for defining extreme precipitation indices. The first method of quantifying the extremes is by using percentiles as a reference, and the second method is governed by using fixed thresholds. There have been so many studies on extreme rainfall quantification by using these two criteria on a global as well as on a regional basis (Rajeevan et al., 2008; Bharti, 2015a; Gujree et al., 2017; Pendergrass 2018). The daily precipitation time series have been extracted from the study region for the calibration period 1969–2018 by defining a precipitation day as when the accumulated precipitation exceeds 1 mm/day (Indian Meteorological Department, 2019). The percentiles 65th, 75th, and 85th are computed based on the precipitation days available for the same calibration period. For fixed thresholds,  $R_{10}$ ,  $R_{20}$ ,  $R_{30}$ ,  $R_{50}$ ,  $R_{5-30}$ ,  $R_{30-50}$ ,  $R_{x1}$  day, and  $R_{x5}$  day indices, have been used where  $R$  represents precipitation event, and the number represents the intensity of the corresponding event. The maximum consecutive wet day (CWD) and consecutive dry day (CDD) spells for each year during the same calibration period have been calculated to get an insight into the rainfall excess and deficit years. To see the variability of these extremes, statistical analysis has been performed on these extreme events on a yearly temporal basis. The overall categorization of extreme precipitation indices is given in the flow chart in Figure 2. For analyzing the trend in these indices over the study region, a simple regression model is fitted to show the trend line in the time series as governed by Eq. (1).

$$y = \alpha + \beta x \tag{1}$$

$Y$  represents the frequency of rainfall index and  $\alpha$  denotes y-intercept,  $x$  is the yearly time series, and  $\beta$  shows the trend line's slope.

**Figure 2** The methodology for quantifying extreme rainfall indices over the study region



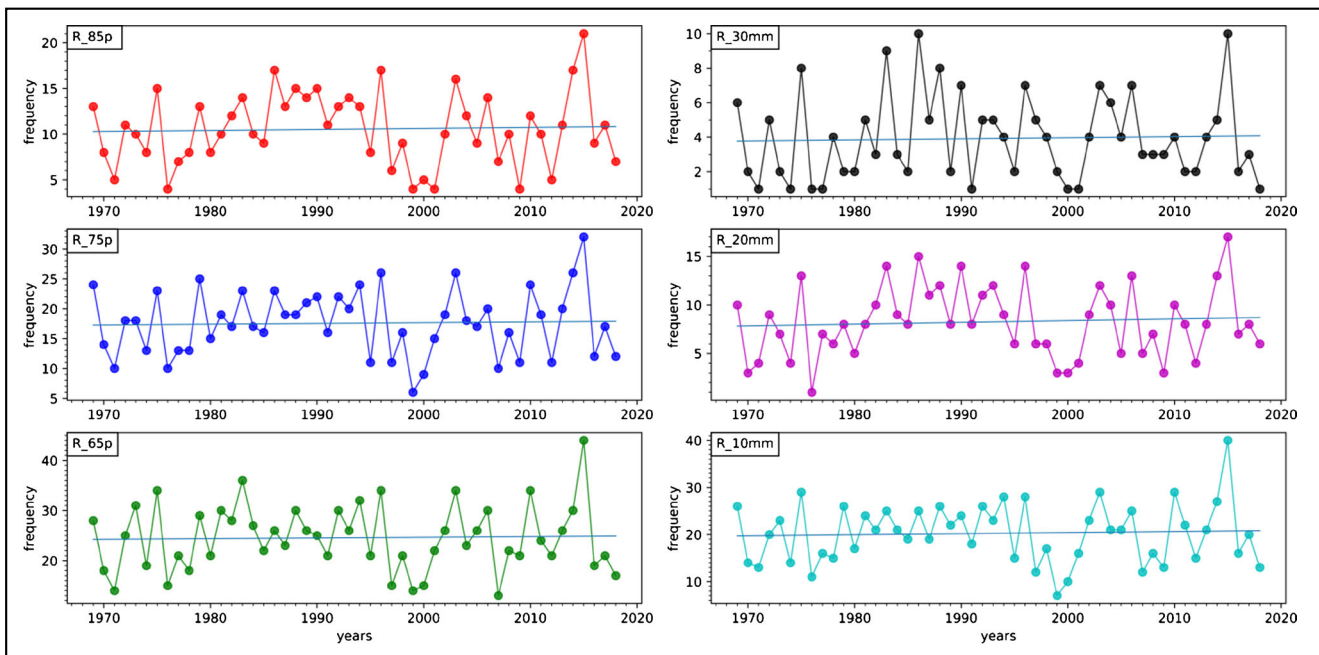
Furthermore, to see the linkage of these extreme rainfall indices with various global oscillations, lag correlation technique (Schmidt et al., 2010) has been used to see the effect of El Niño southern oscillation (ENSO), Atlantic multidecadal oscillation (AMO), and Pacific decadal oscillation (PDO) on these rainfall extremes.

## Results

### Trend analysis

Trend analysis has been carried on all the extreme precipitation indices based on percentile and fixed thresholds over the study region. Figure 3 depicts the time series of frequencies of rainfall based on percentile thresholds (85p, 75p, and 65p) and fixed thresholds (30 mm, 20 mm, and 10 mm). It is seen that there is a slight increasing trend in frequencies of all the extreme rainfall indices from 1969 to 2018. The highest peak in the precipitation frequencies is seen during 2014, which indicated that the extreme rainfall is quantified by these thresholds as the study region was under flood during September 2014 with more than four continuous days of heavy precipitation resulted in massive devastations (Rao et al., 2016; Vitalani, 2017) while the year of 1999 exhibits the lowest frequency of extreme rainfall indices which validated that this year was under severe drought as revealed by (Parvaze et al., 2018).

To quantify the peak and medium precipitation events over the study region, three categories of fixed thresholds have been used based on daily rainfall of 50 mm, 30–50 mm, and 5–30mm thresholds. The frequency of extreme precipitation indices based on these fixed thresholds is shown in Figure 4, which depicts that one of the extreme precipitation indices:  $R_{50}$  shows a decreasing

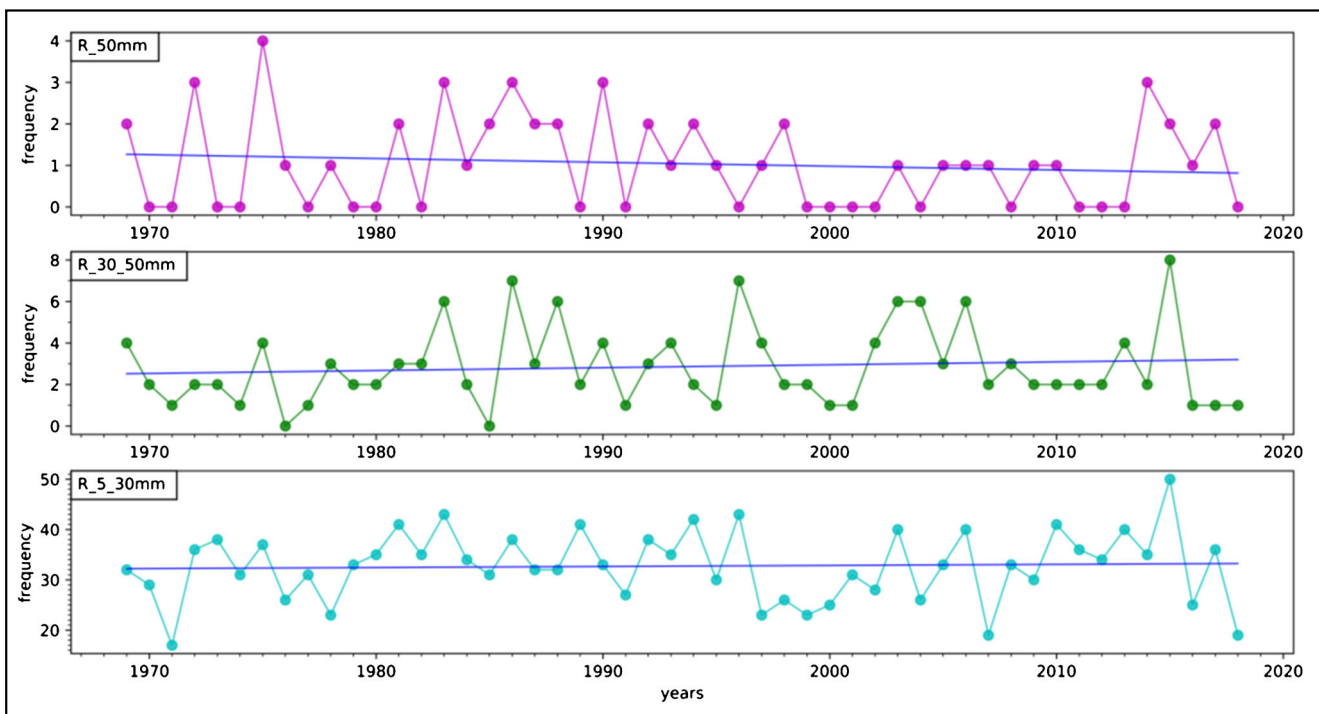


**Figure 3** The time series of frequencies of extreme precipitation indices based on a percentiles ( $R_{65}$ ,  $R_{75}$ , and  $R_{85}$ ) and fixed thresholds ( $R_{10}$ ,  $R_{20}$ , and  $R_{30}$ ) over the study area

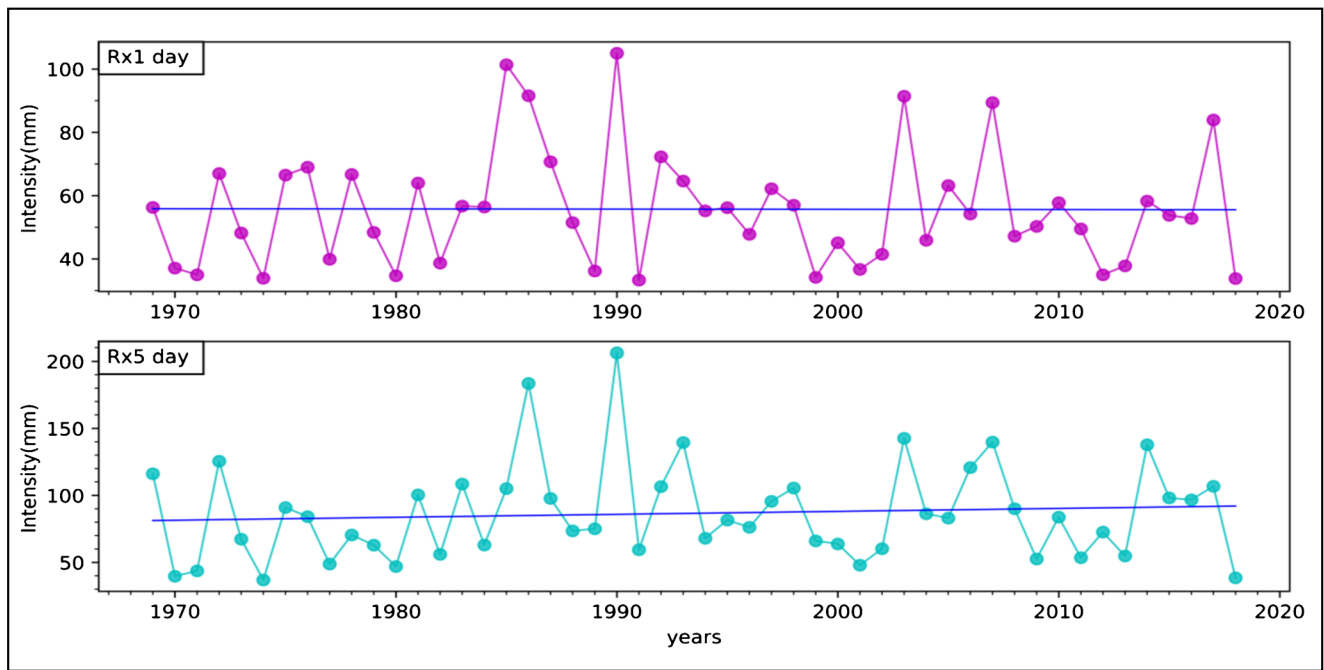
trend while the other two indices are based on  $R_{30}$ – $50$  and  $R_{5}$ – $30$  show an increasing trend during the study period.

Also, to quantify the intensity of 1-day and 5-day maximum extreme precipitation indices, the time series for the intensity of 1-day ( $R_{x1}$  day) and 5-day ( $R_{x5}$  day) maximum precipitations is shown in Figure 5. The time series of  $R_{x1}$  day is quite haphazard, showing no significant trend between 1969 and 2018. However,

it can be revealed that the  $R_{x5}$  day shows an increasing trend in recent decades. To categorize the rainfall excess and deficit years over the study region, CWD and CDD for the same study period have been calculated, as shown in Figure 6. On analyzing the frequency of CDD, it is found that the peak of CDD goes to 70 days in 1998 and a minimum value of 10 days in 1991



**Figure 4** The time series of frequencies of rainfall indices based on fixed thresholds, i.e., 50mm, 30–50mm, and 5–30mm

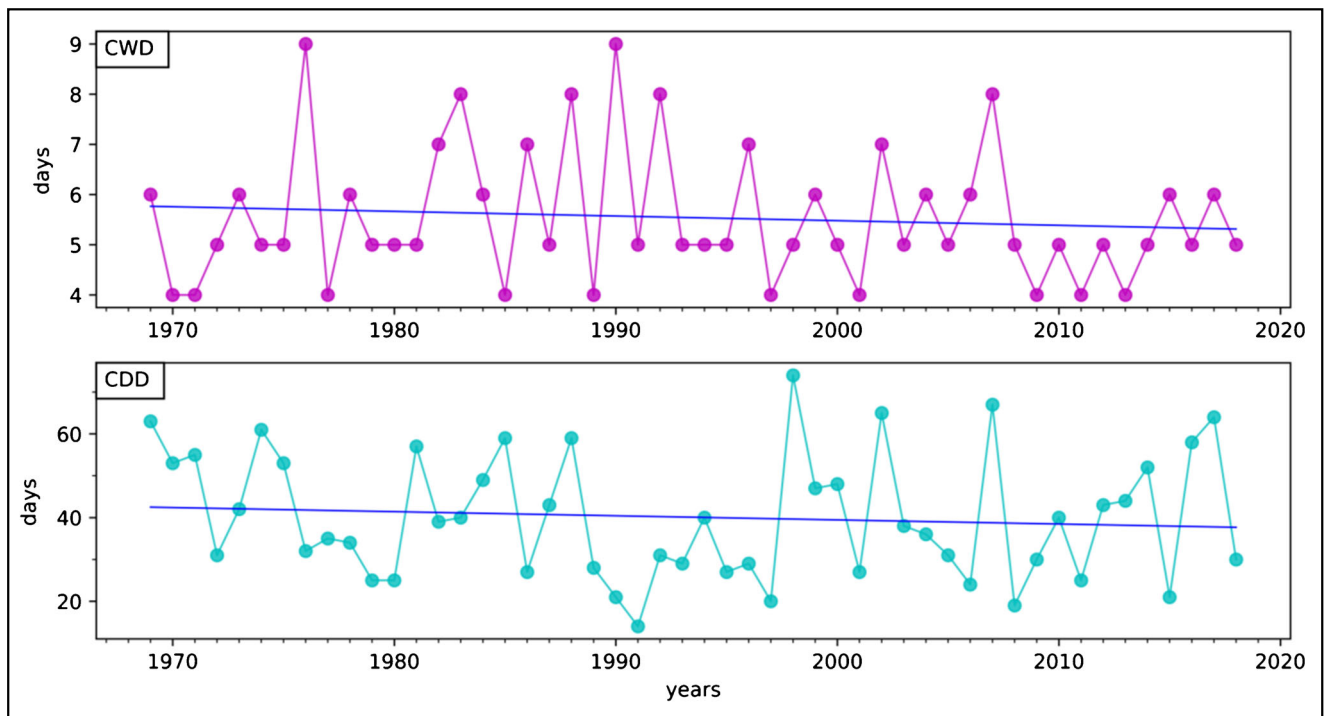


**Figure 5** The time series of maximum Rx1 day and Rx5 day over the study area where Rx1 day and Rx5 day indicate the intensity of maximum 1-day and 5-day maximum rainfall

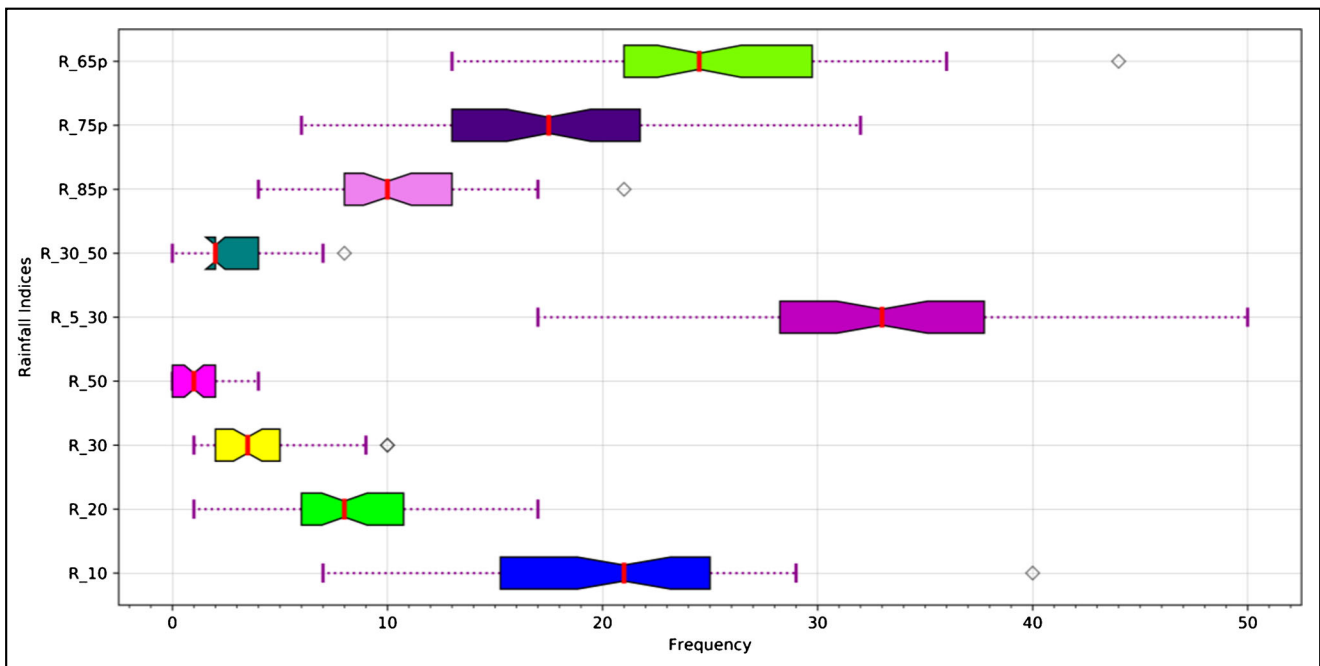
(Figure 6). On the other hand, the maximum wet spell goes to 9 days between 1979 and 1990.

Apart from this, the variability of CCD is more as compared to CWD as revealed in Figure 6. Hence, it can be revealed that the variability of CDD is high, indicating the possibilities of more future drought years over the study region, as

also shown by Parvaze et al. (2018). The years (1999, 2000, 2001, 2007, and 2016) were under drought, and during these years, the frequency of CDD is maximum indicating long dry spells over the study region as revealed by the second panel in Figure 6. The trend of CWD is decreasing, and the trend of



**Figure 6** The time series of maximum continuous wet days (CWD) and continuous dry days (CDD) over the study region



**Figure 7** The statistics of all the rainfall indices over the study region

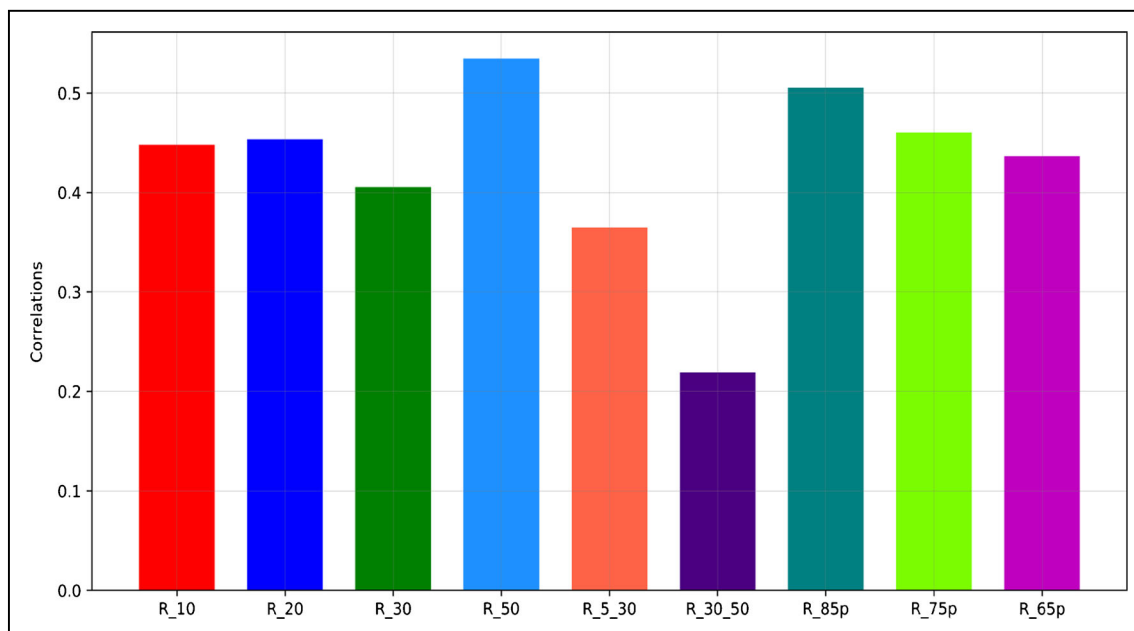
CDD has also decreased for recent years leading to the conclusion that precipitation is becoming uniform in seasons.

The statistics of all the extreme rainfall indices are shown in Figure 7, revealing that R\_5–30 extreme rainfall indices have the highest mean value, while low mean frequency is obtained by R\_50 depicting that most of the precipitation is between 5 and 30 mm over the region. Also, R\_50 events are rare and can cause a flood-like situation over the study region. The frequency of the R\_5–30 with a maximum value of 50 and a minimum value of 17 means that a year can also experience 50 such events

depicting the year as rainfall excess year. Hence, it can be concluded that the study area experienced rainfall in the range of 5–30 mm/day. The other rainfall frequency also shows a variation with a mean ranging from 2 to 24, as revealed in Figure 7.

### Correlation of rainfall indices with the discharge

The correlation analysis has been carried out on the yearly frequency of extreme precipitation indices with the study region’s yearly total discharge time series over a calibration



**Figure 8** The correlation coefficients of yearly discharge time series of the nearest gauge station with all the rainfall indices over the study region

period from 1969 to 2018 to see the interference of extreme rainfall on discharge, which is shown in Figure 8. From our analysis, it can be observed that a maximum correlation greater than 50% pertains to the R\_50 while a minimum correlation of 23% for rainfall about R\_30–50, and hence it can be concluded with the statement that precipitation greater than 50 mm in a day can bring the flood-like situation in the study region. The precipitation indices based on other thresholds also attain a fair correlation with the discharge, as shown in Figure 8. The R\_10- and R\_20-based extremes show nearly the same correlation with the discharge data as the yearly frequencies of both the extremes indices are similar to a greater extent, depicting that these two indices can reveal a similar correlation with the discharge. On the other hand, the R\_85p, which is the rainfall above the 85th percentile of the daily rainfall with a reference period (1969–2018) and is considered as the uppermost percentile for defining extreme rainfall events reasonable responsible for floods, shows a nearly similar correlation with the fixed threshold-based extreme rainfall (R\_50) which in turn is also considered as the extreme case of rainfall. Hence, it can be disclosed with the statement that extreme rainfall, whether based on the higher percentile of daily rainfall or higher fixed rainfall thresholds, will give fair results about the possibility of floods by these extremes.

### Relation of rainfall indices with the global oscillation indices ENSO, AMO, and PDO

The precipitation over the study region is mainly controlled by two weather systems pertaining to the winter and summer

seasons. Winters are primarily governed by western disturbances (WDs), and the summer season is affected by Indian summer monsoons. Hence, the variability of these two weather systems will significantly affect the extreme precipitation indices over the study region. Thus, finding the correlation of these two systems with the global oscillations will generally help to predict and forecast the extreme rainfall over this region. The lag correlation technique has been evolved to find the governing relationship of ENSO, AMO, and PDO with the extreme rainfall indices over the region. The lag correlation between the SST of the Niño 3.4 region and the frequencies of rainfall indices is shown in Figure 9. It is observed that the rainfall, which is concerned with R\_20, shows a maximum correlation with the El Niño phase of ENSO. It is positively correlated with the April SST over this region with a correlation value of greater than 0.35. The minimum correlation is shown in R\_50 events, i.e., the precipitation governed by the R\_50 index is rare over the study region. On the other hand, the rainfall based on other percentiles shows a positive correlation with SST over Niño 3.4 area for lag0, while a few months show a negative correlation with the R\_30- and R\_50-based rainfall by lag1; that is, previous year SST anomalies of January, February, March, and April do not affect R\_30 and R\_50 precipitations.

As far as AMO is concerned, the frequency of all the rainfall indices shows a negative correlation with the AMO index in lag0, but R\_30 shows an alternate positive and negative correlation in both lag1 and lag0 conditions. In contrast, R\_30–50-based precipitation shows a positive correlation with the AMO index, as revealed in Figure 10.

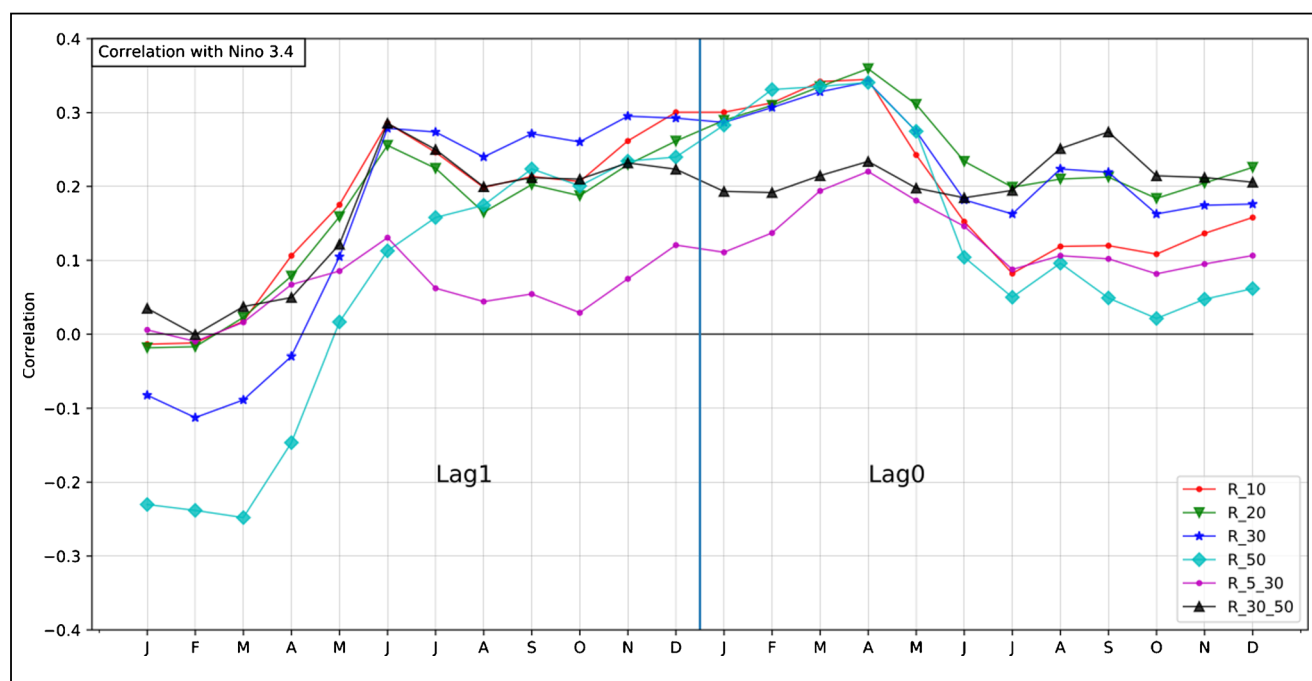


Figure 9 The lag correlation of all the rainfall indices with the Niño 3.4 index



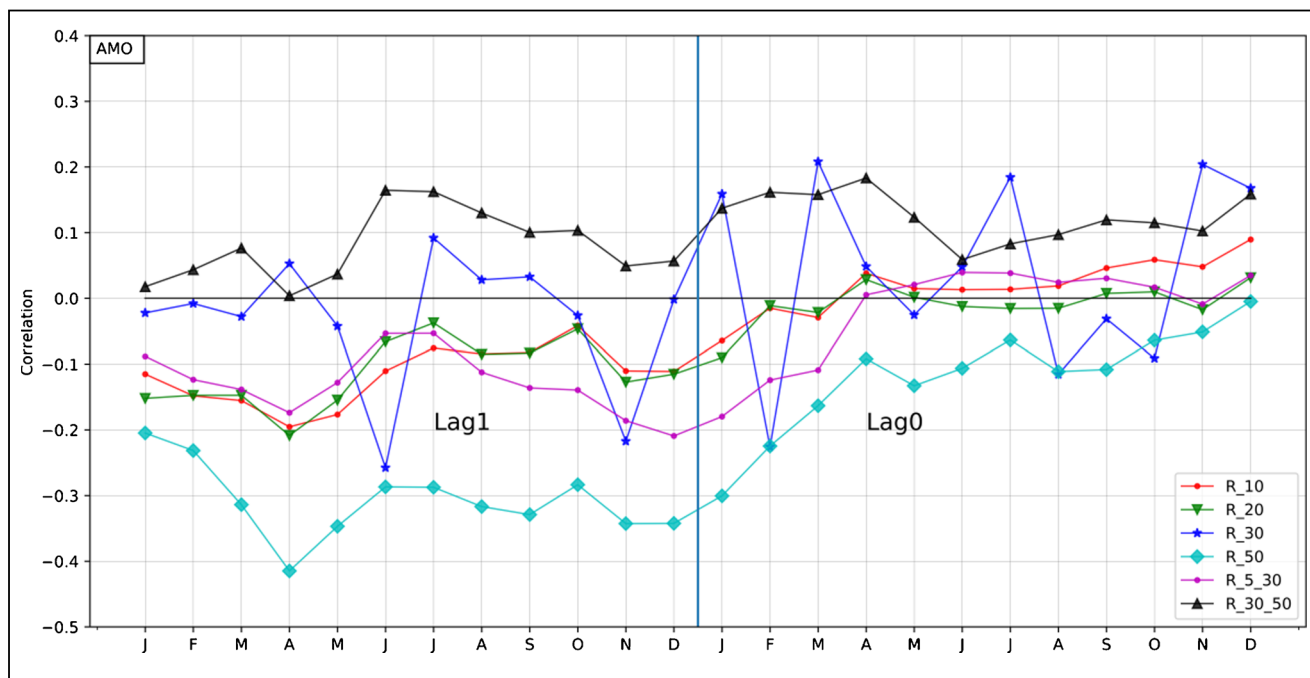


Figure 10 The lag correlation of all the rainfall indices with the AMO index

Apart from this, the Pacific decadal oscillations also affect the frequency of various rainfall categories over the study region, as revealed in Figure 11. In lag1 conditions, the rainfall events are positive correlated with PDO for all the months. Certain indices like R\_50, R\_10, and R5\_30 show a negative correlation with PDO during January, February, March, and April.

### Discussion

Extreme precipitation accompanying an increase in urbanization is considered the main culprit for most of the floods both regionally and globally (Duan et al., 2017). With an increase in anthropogenic activities, the chances of more unprecedented extreme precipitation events are continuously increasing worldwide, leading to more threats of a natural disaster,

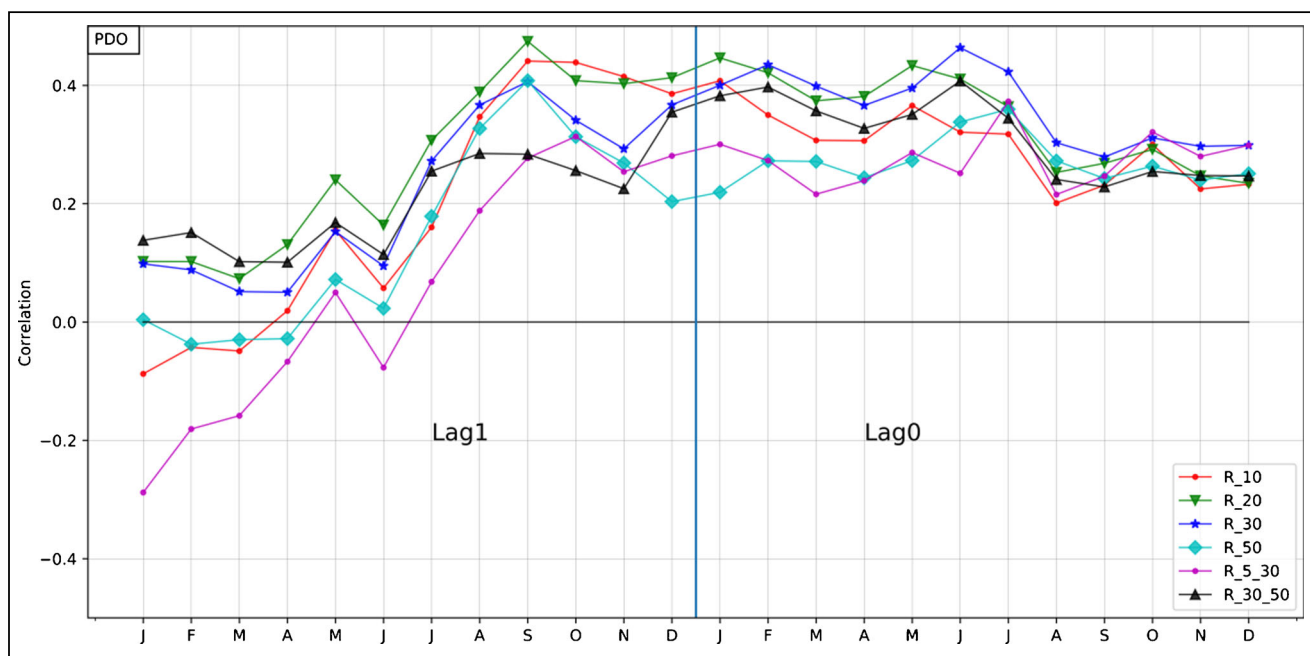


Figure 11 The lag correlation of all the rainfall indices with the PDO index

bringing societal degradation. The main motive of this study is to quantify the extreme precipitation indices over Srinagar city in central Kashmir (India), based on fixed and percentile thresholds in connection with global oscillation for better forecasting systems. It is found that the daily precipitation falls under the category of 5 to 30 mm, with precipitation greater than 50 mm is considered as the backbone for creating flood-like situations over the study region. The trend analysis reveals that extreme precipitation events manifest an increasing trend while CDD is showing a decreasing trend confirming a high probability of future floods. The El Niño and PDO show a positive correlation with all extreme precipitation indices in zero-lag primarily, while AMO only positively affects R<sub>30–50</sub> mm. For understanding the mechanism of a flood, the extreme precipitation indices are quantified in association to global oscillation and discharge, and apart from this, rainfall deficit and excess years have also been extracted over the study region.

The study area is considered one of the fastest-growing urban areas in the western Himalayan region (Kuchay et al., 2016). An increase in urbanization leads to more exposure to various types of floods (Handayani et al., 2020). The most vulnerable area to floods consists of 46% of Srinagar city incorporating 33 municipal wards which are quantified as potential centers for floods, while other areas fall in moderate to low-level risk (Alam et al., 2018). Keeping in view the vulnerability of this area to unprecedented floods, the government of Jammu and Kashmir has planned the disaster management plan for the city which mainly includes the preventive and strategic measures which can reduce the ramification of upcoming floods and the implementation of following strategies like incorporating disaster management into the development, identification of areas vulnerable to disaster, building permission, strengthening of existing structures, and training of professional, information, education, and communication (IEC) programs. While taking these points in mind, this study can draw its impact on the new ideas that can be developed in flood management and flood forecasting systems, which can be used in managing the water resources over the study region. As flood management in flood-prone areas is very complex due to the involvement of many factors like climate change, urbanization, increase in intensity and frequency of unprecedented events, and predictability of downpours. The policymakers of the society have to evaluate the social and dynamics of the population of the study area to go in depth regarding the management of floods. The management of floods includes both structural measures like making dams and levees and non-structural measures such as improvements in flood forecasting, early warning systems, and participation of the internal community in flood-risk management which will give better results for decreasing the catastrophe of a natural disaster. Hence, it can be concluded that once we know the actual spatiotemporal variability of extreme precipitation over a study region and its possible mechanism, the policymakers of society can be thoughtful to change the

governing policies accordingly regarding the management of a natural disaster like quantifying the most flood vulnerable zones, prepare the floods channels that can retain maximum amount discharge during floods, improve the embankments of the connecting rivers to avoid the possible breaches and inundations of the nearby areas, fasten the process of dragging of silt from the main rivers, prepare a substantial body of disaster management systems that can withstand with the society on a natural disaster, and prepare water transport so that emergency services cannot be degraded during floods.

## Conclusion

The spatiotemporal variability of rainfall is contemplated as a predominant approach for quantifying and forecasting extremes over a given region. The primary goal of this research is to comprehend the spatial-temporal variability of extreme precipitation indices associated with global oscillations over Srinagar Kashmir, India. The results showed that the rainfall indices are positively correlated with El Niño and PDO oscillations for lag0. Whereas AMO positively correlates R<sub>30–50</sub> for lag0 and lag1, all other indices do not show an evident variation with AMO. It can be also concluded that R<sub>50</sub>-based extreme precipitation shows maximum correlations with the discharge. Thus, precipitation with that intensity can also cause flood situations in the study area. Trend analysis has been conducted on all the rainfall indices over the study region and on observation, it can be figured that all the indices based on percentile thresholds and fixed thresholds show a slightly increasing trend; that is, the frequency of extreme precipitation is increasing continuously, leading to the threat of more future floods. In addition, the study region mainly experiences daily precipitation in the range of 5–30 mm, with 50-mm daily precipitation reasonably responsible for a flood-like situation.

The study had addressed the policies of water resources management as flood management over such vulnerable areas is complex to deal with. Hence, it can be summarized that policymakers of the society have to adopt both structural and non-structural measures for flood management to decrease the potential impacts of a natural disaster on a society. It is necessary to appropriately address the mechanism governing the increasing frequency of extreme rainfall to predict future floods and decrease the intensity of these catastrophic events.

## Declarations

**Conflict of interest** The authors declare that they have no competing interests

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