Climate Change Impact on Extreme Precipitation Events in Pakistan; A Case Study of Hindu Kush Mountains

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Abstract

For this study, we used 30-year (1991-2020) datasets of daily precipitation from ten weather stations in the Hindu-Kush Mountains of Pakistan to analyze the historical change in the extreme precipitation events. To accomplish this, the RClimDex model was used, while trend and slope assessments were conducted using the Mann-Kendall test and the Theil-Sen slope estimator, respectively. Changes in the extreme precipitation events were assessed using eight commonly used precipitation indices. The findings reveal a noteworthy reduction in the cumulative yearly precipitation amount (PRCPTOT) with distinct decreasing trend, about -5.31 mm/year. The extreme precipitation indices (one day maximum (RX1Day), consecutive five days maximum (RX5Day), 95 percentile precipitation (R95p), and 99 percentile precipitation (R99p)) showed decreasing trends of extreme precipitation events in the region. However, the number of consecutive dry days (CDD) was increased, conversely the number of consecutive wet days (CWD) indicated a decreasing trend over the past three decades. Notably, the frequency of wet days having precipitation amount ≥ 25 mm per day (R25) showed a significant reduction in the frequency of heavy precipitation events. The results of this study show that extreme precipitation occurrences in Pakistan's Hindu-Kush mountains have been less severe, less frequent, and less widespread over the

last 30 years.

Key words: Extreme Precipitation; Hindu-Kush Mountains; Trends Analysis; RClimDex Model; Mann-Kendall Test

I. Introduction

Precipitation is a crucial element within the hydrological cycle, exhibiting significant spatio-temporal variability on a global scale. Variations in precipitation have a major impact on both the natural environment and human life [1]. Over the past few decades, it has become increasingly evident that there has been a shift in the durations, quantity and return period of precipitation extremes, particularly due to climate change caused by human activity [2]. The hydrological regime and socioeconomic well-being of a region can be greatly impacted by extreme precipitation events [3]. Extreme precipitation events has the capacity to provide substantial consequences, such as the possibility of flooding and landslides, which can lead to severe damage to infrastructure, transportation systems, communication networks, and human lives [4].

In particular, the mountain ranges are at risk from the adverse effects of climate change because of their central role in Earth's climatic system [5]. Water resources, ecosystems, and social and economic systems are all susceptible to changes in precipitation patterns. Water resources, ecosystems, and social and economic systems are all susceptible to changes in precipitation patterns. In order to assess the impacts of climate change, identify potential hazards, and design suitable adaptation strategies, it is imperative to possess a comprehensive assessment of the historical patterns and fluctuations in both total and extreme precipitation within mountainous areas. The northern highlands of Pakistan are an example of a subtropical highland region that has not yet had sufficient research on the historical variations in total and exceptional precipitation occurrences.

The agricultural sector in Pakistan significantly depends on a reliable and abundant water supply derived from precipitation [6]. The potential impact of alterations in precipitation patterns on the agricultural productivity of the nation is a matter of significant concern [7]. Extreme precipitation events can majorly affect Pakistan's hydrological regimes and the country's economy and society. These occurrences are caused by a convergence of humid air from the Arabian Sea and the Bay of Bengal, which is lifted by the orographic forces as it passes through the Hindu-Kush and Himalayan Mountain ranges [8]. The susceptibility of the mountainous regions of Pakistan to such intense precipitation occurrences is mostly attributed to the rugged topography and escalating anthropogenic activities in the area. It is anticipated that there would be an increase in the intensity and frequency of extreme precipitation events due to climate change, with the potential for these impacts to be further exacerbated in the future [9].

Numerous studies have been conducted to assess the variations in intense precipitation occurrences throughout various geographical areas on a global scale [10,11]. Despite a general trend towards increased frequencies of extreme precipitation events, there is significant geographical and temporal variability in both the frequency and intensity of such events across diverse climatic regions. Recent studies have documented a growing occurrence of intense precipitation events in several regions, including the Tibetan Plateau [10], South Asia [12], Central Asia [13], and Europe [14]. Over the past few decades, there has been an observed rise in the frequency and intensity of extreme precipitation events in Mainland China. According to a study, Bangladesh has shown a notable increase in occurrences of extreme precipitation events [15]. Nevertheless, it has been shown in Pakistan that there is a declining pattern in event-based extreme precipitation for different return periods [16]. According to the existing body of evidence, it is evident that climate change has led to an augmentation in the temporal and spatial variability of precipitation extremes worldwide.

The examination of temporal and spatial changes in extreme precipitation events in Pakistan is of utmost importance due to the significant impact they have on the country's economy and population. The occurrence of flooding and other types of intense precipitation can lead to detrimental effects on infrastructure, including destruction and impairment of transportation and communication systems. Consequently, these events can have severe consequences, such as human casualties and material losses. Furthermore, it is worth noting that instances of intense precipitation can further intensify the issue of limited water availability and contribute to the problem of inadequate access to food, especially in rural regions heavily reliant on agriculture for sustenance. To effectively address the devastating consequences of precipitation extremes, it is crucial to get a full comprehension of the frequency and intensity of these occurrences, with their potential origins and ramifications. Numerous previous research has investigated the changes in extreme precipitation occurrences in Pakistan [[17,18], there has been a notable absence of research specifically focused on investigating the changing behavior of precipitation extremes in the Mountains of Pakistan. The purpose of this study is to analyze the spatial and temporal patterns of extreme precipitation events in the Hindu-Kush Mountains of Pakistan during the past three decades, based on the provided context. This study sets itself apart by employing a comprehensive temporal scope and integrating supplementary extreme indices. The findings of this study are expected to offer valuable insights to both governmental and non-governmental groups engaged in the improvement of disaster risk management and the formulation of adaptation plans within the country.

□. Materials and Methods

Study Area

In order to examine the effects of climate change on severe precipitation over the past 30 years, we focused on the Hindu-Kush Mountains (Figure 1), one of the biggest mountain ranges in South Asia. The westerlies circulation system affects the western part of this range with respect to precipitation, whilst the monsoon circulation system primarily covers the eastern half. The winters here are typically mild, and the snow/rain season begins in July and lasts all the way into September. The spatial variability map of average yearly precipitation in shown in Figure 2, and the spatial variation of mean yearly temperature in presented in Figure 3.

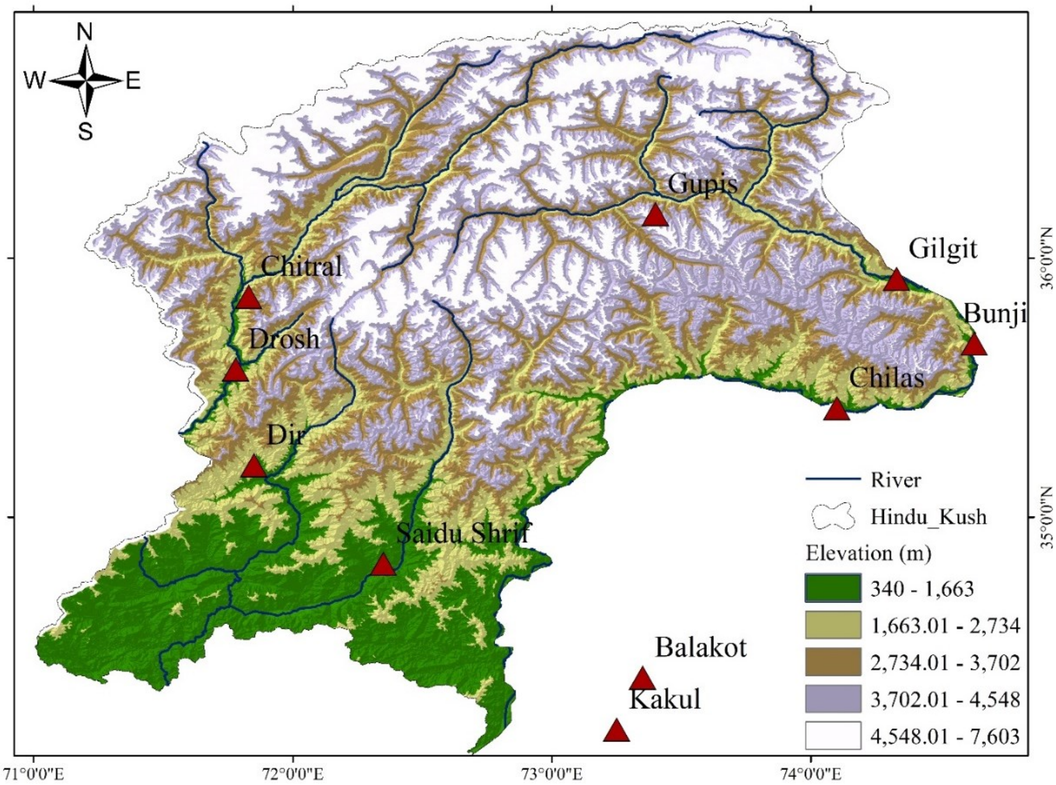


Figure 1. Location ma p of Hindu-Kush Mountains in Pakistan.

The magnitude of precipitation varies greatly over the domain. Precipitation is often heavier in the southern half of the range and lighter in the eastern part. There is a sharp north-to-south gradient in elevation within this range, from an average of 7,603 meters above sea level (a.m.s.l.) to an average of 3,403m a.m.s.l.

The Pakistan Meteorological Department (PMD) provided the daily precipitation records from ten in-situ weather stations in order to accomplish this study. Strict selection criteria were used to assess extreme climatic indices using station data. The research was conducted in strict accordance with the following criteria: (i) monthly datasets were regarded as complete if they contained a maximum of five missing days; (ii) yearly datasets were regarded as complete if every month fulfilled criterion (i); and (iii) a station's data was regarded as complete if in its whole record there were no more than five missing years. It is noteworthy that PMD had previously guaranteed the accuracy and uniformity of these records. Table (1) provides information on the elevation and locations of the weather stations.

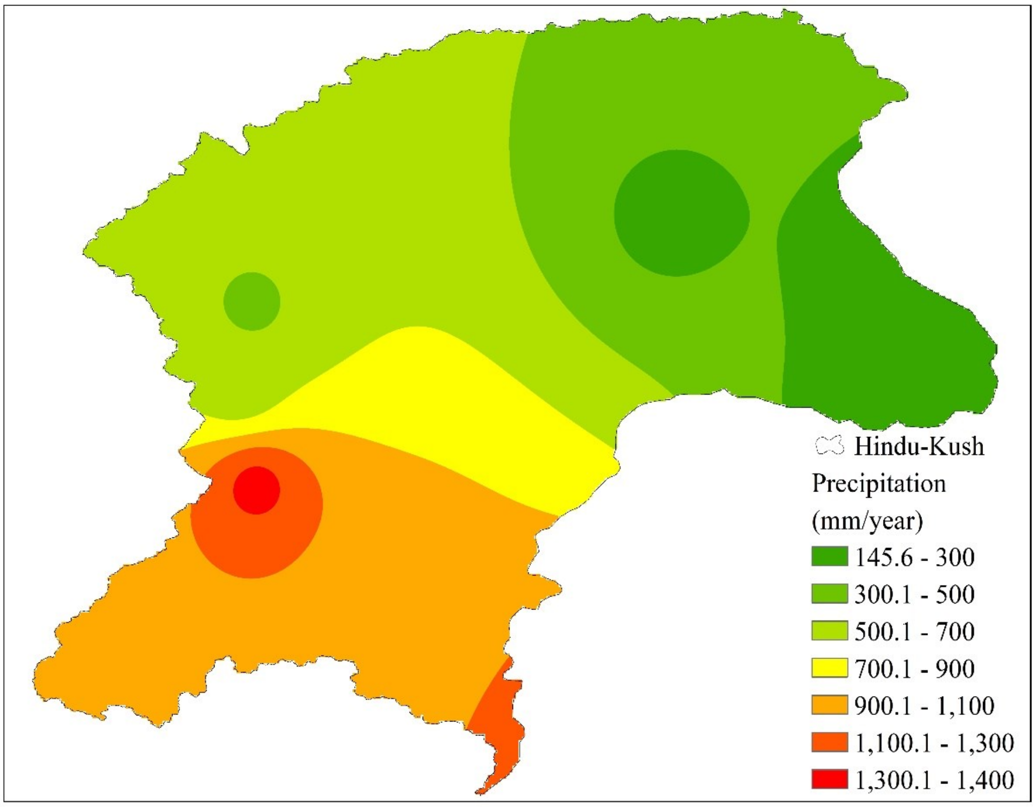


Figure 2. Spatial variability map of yearly average precipitation (for the period of 1999-2020) in the Hindu-Kush Mountains of Pakistan.

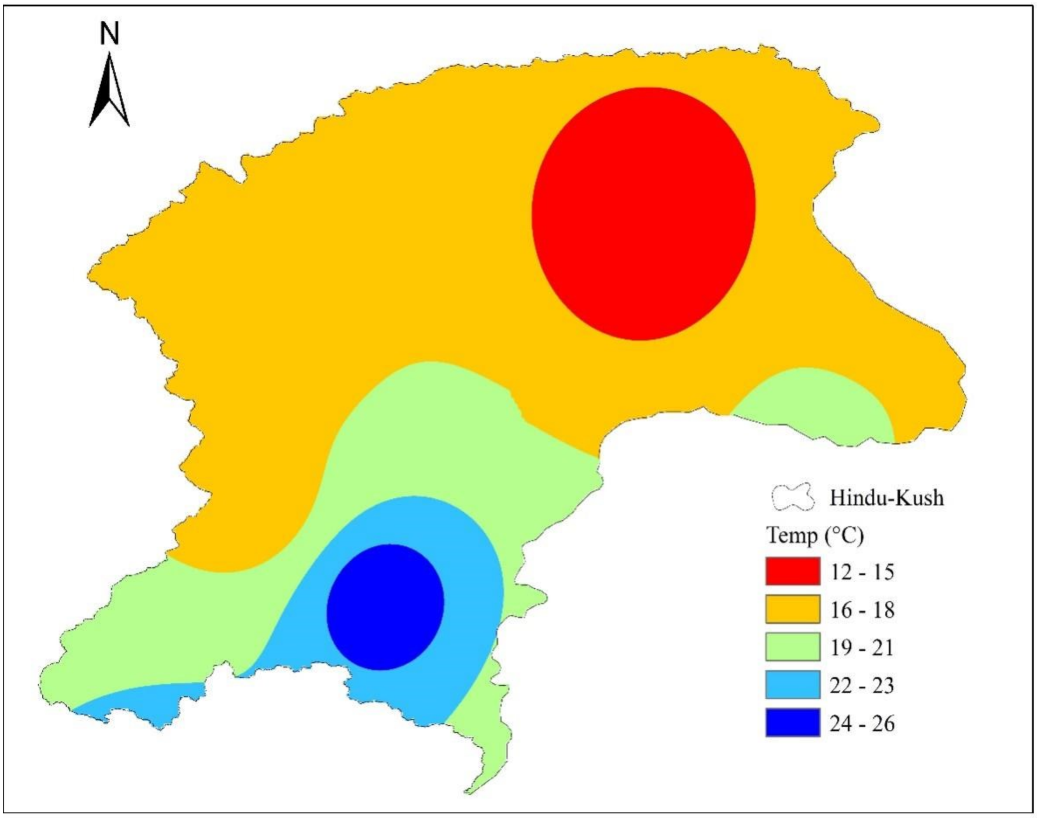


Figure 3. Spatial variation of annual average temperature (during 1990-2020) in the study domain.

Sr. No.	Station	Long (dd)	Lat (dd)	Elevation (m)	Average Annual Precipitation (mm)
1	Balakot	73.359	34.379	981	1475.03
2	Bunji	74.628	35.667	1470	160.73
3	Chilas	74.101	35.419	1251	196.82
4	Chitral	71.819	35.836	1500	466.02
5	Dir	71.857	35.209	1370	1364.90
6	Drosh	71.766	35.557	1465	549.49
7	Gilgit	74.327	35.916	1457	145.60

8	Gupis	73.403	36.168	2156	248.92
9	Kakul	73.246	34.177	1309	1312.16
10	Saidu Shrif	72.351	34.817	970	1036.64

Table 1. Details of weather stations used in this analysis.

Eight indices developed according to the Expert Team on Climate Change Detection and Indices (ETCCDI) project were used to analyze the extreme precipitation at each site. The ETCCDI developed the RClimDex programme, which was used to process the data. In order to ensure that there was no discontinuity in the data series of the R95p and R99p percentile-based indices at the start or end of the study period, the bootstrapping approach was used to estimate the values for the time series of these indices.

The study incorporates the eight extreme precipitation indices based on the Expert Team on Climate Change Detection and Indices (ETCCDI), as outlined in Table 2. The PRCPTOT, RX1Day, RX5day, R95p, R99p, R25mm, CDD, and CWD indices are used to assess the intensity of heavy rainfall occurrences.

Table 2. Details of considered extreme precipitation indices.

Sr. No.	Symbol	Index	Description
1	CDD	"Consecutive dry days"	"Maximum number of consecutive days with RR<1 mm"
2	CWD	"Consecutive wet days"	"Maximum number of consecutive days with RR≥1 mm"
3	R25	"Number of heavy precipitation days"	"Annual counts of days when PRCP≥25 mm"
4	R95p	"Very wet day precipitation"	"Annual precipitation total of RRN95th percentile"
5	R99p	"Extremely wet day precipitation"	"Annual precipitation total of RRN99th percentile"
6	RX1day	"Maximum 1-day precipitation"	"Monthly maximum 1-day precipitation"
7	RX5day	"Maximum 5-day precipitation"	"Monthly maximum 5-day precipitation"
8	PRCPTOT	"Total annual precipitation"	"Total annual precipitation of rainy days (RR≥1 mm)"

A non-parametric Modified Mann-Kendall (MMK) Test was utilized for the analysis of linear trends in precipitation indices. This particular method has a better tolerance for outliers within a series and works well with data that has non-normal distributions. It also has a higher level of resilience to extreme values. The assessment consisted of an examination of patterns of total precipitation at yearly scale, as well as an analysis of trends in extreme precipitation indices on regional scale. Examining the outputs of the trend analysis performed at each gauging station was a necessary step in determining the spatial variation of precipitation extremes that occurred in the area under study.

In 1998, Hamed and Rao modified the Mann-Kendall test to account for the adjusted variance of the Mann-Kendall statistic S. The MMK test, an adaptation of the Mann-Kendall test, was developed as a result of this revision. The following are the equations that are used to calculate S, Z, the variance of the standardized test, and V*(S), the corrected variance:

$$S = \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} \mathrm{sgn}(x_k - x_j) \quad (1)$$

$$\mathrm{sgn}\ (x_k - x_j) = \begin{Bmatrix} 1 & \text{if } x_k - x_j > 0 \\ 0 & \text{if } x_k - x_j = 0 \\ -1 & \text{if } x_k - x_j < 0 \end{Bmatrix} \quad (2)$$

$$V(S) = [n(n-1)(2n+5) - \textstyle\sum_t t(t-1)(2t+5)/18] \quad (3)$$

$$V*(S) = V(S)\mathrm{Cor} \quad (4)$$

where

$$\mathrm{Cor} = 1 + \frac{2}{n(n-1)(n-2)} \sum_{i=1}^{n-1} (n-1)(n-i-1)(n-i-2)\rho_s\,(i) \quad (5)$$

$$Z = \begin{Bmatrix} \frac{S-1}{\sqrt{V(S)}} & \text{if } S > 0 \\ 0 \ \text{ if} & S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & \text{if } S < 0 \end{Bmatrix} \quad (6)$$

where the timeseries values are represented by xj and xk, with k being higher than j. The variable t stands for time period, n indicates the total count of measurements, and $\rho_s(i)$ represents the significant autocorrelation function of the ranks of the observations. When Z has a value in the positive range, it suggests an upward trend, whereas when it has a value in the negative range, it indicates a downward trend. The significance of the trend was evaluated at a level of significance equal to or greater than 5%.

The Theil-Sen (TS) method was utilised so that a precise evaluation of the slope of the trend could be accomplished. The following computation was utilised in order to establish the slope in accordance with the TS method:

$$T_i = \frac{x_j - x_k}{j - k} \tag{7}$$

where x_j and x_k show the values at time intervals j and k, respectively.

$$Q_i = \begin{cases} T_{\frac{N+1}{2}} & \text{N is odd} \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right) & \text{N is even} \end{cases} \tag{8}$$

□. Results

1. Trends analysis of total and extreme precipitation events in the Hindu-Kush Mountains

The analysis of precipitation changes in the Hindu-Kush Mountains of Pakistan was conducted using historical records of annual precipitation spanning a period of 30 years. Figure 3 (a) illustrates the linear pattern observed in the cumulative annual precipitation. The study's findings indicate a prevailing pattern of decreasing annual precipitation. The yearly rate of reduction was around 5.31 mm/year, as shown by a Z-score of -2.43. The statistical analysis revealed that the observed decreasing trend was statistically significance at the 95% confidence level.

Over the period of past 30 years, the number of consecutive dry days (CDDs) was increased slightly, however, the increasing rate (0.03 days/year) was statistically non-significant. The CWD showed a decreasing trend at the rate of -0.01 days/year (Figure 3b). The observed trend of CWD was also statistically non-significant (Figure 3c). On the other hand, all other considered indices (R25, R95p, R99p, RX1Day, and RX5Day) of extreme precipitation events showed statistically significant decreasing trends. The highest decreasing rate was shown by R95p (at the rate of -3.70 mm/year). Overall, results of the studied indices revealed that the frequency of extreme precipitation events was decreasing over the past three decades in the Hindu-Kush Mountains of Pakistan. However, the frequency of dry days was increased over the same duration.

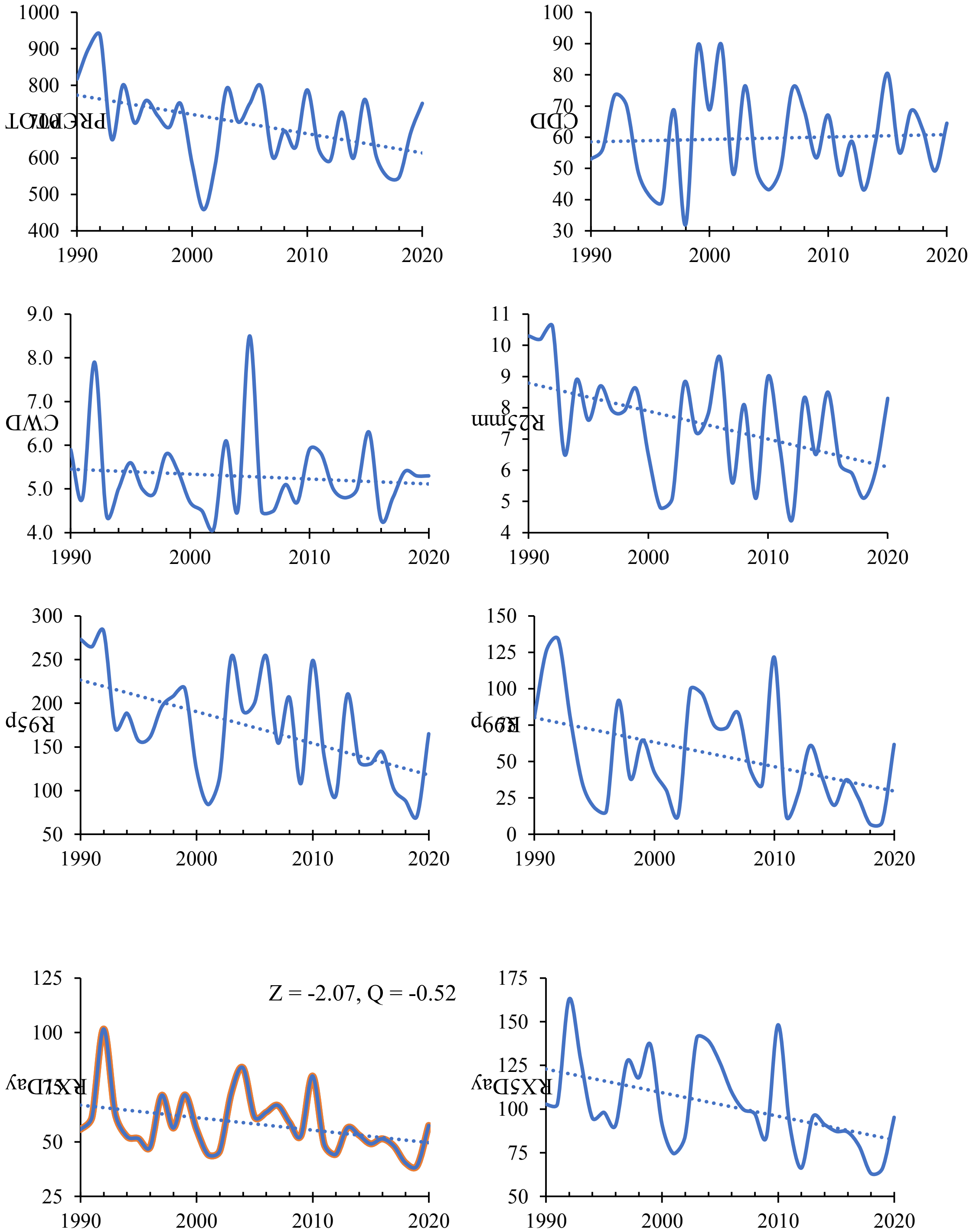
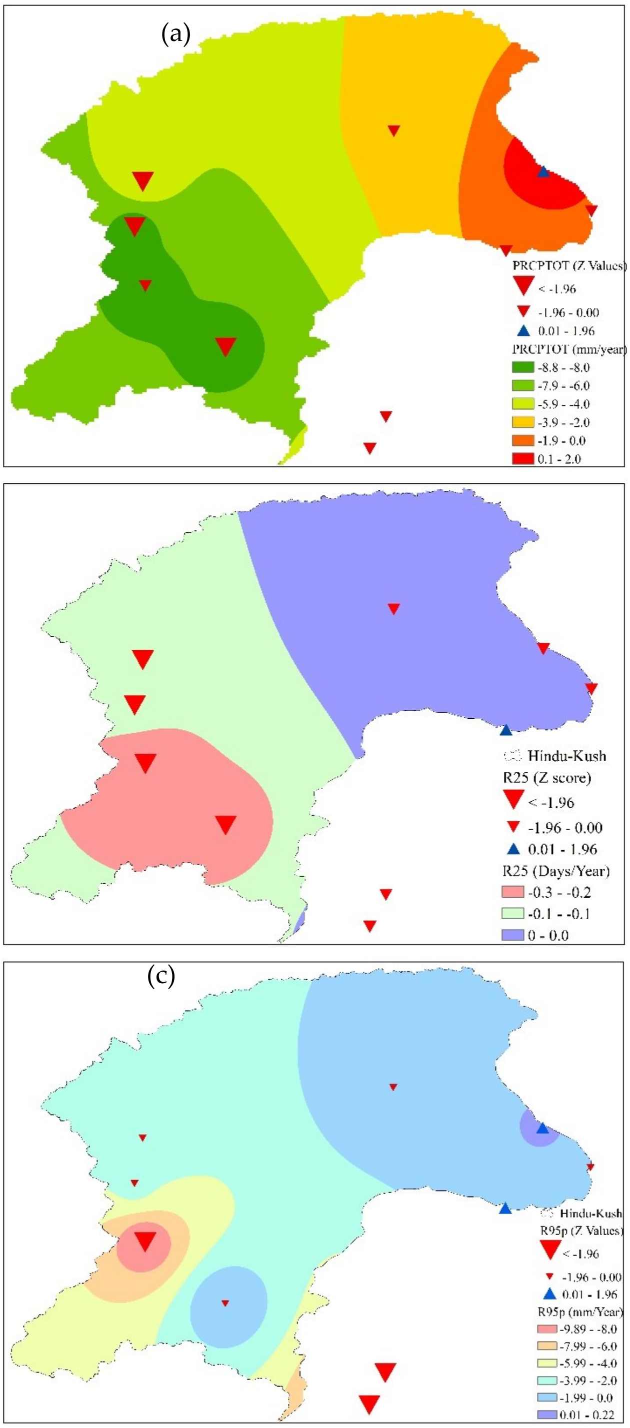


Figure 4. Linear trends in the extreme precipitation indices over the period of 1990-2020.

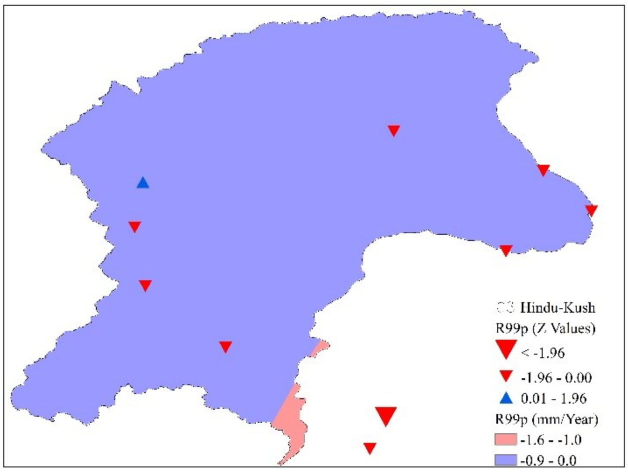
2. Spatial Changes in the Extreme Precipitation Indices

The spatial changes in the rate of changes of extreme precipitation indices were analyzed using Arc-GIS software. For the preparation of maps, the Inverse Distance Weightage (IDW) interpolation technique was adopted. Figure 5 displays the spatial distribution maps of the rate of changes in the precipitation indices and also the results of the MK test statistics (Z values).

(b)

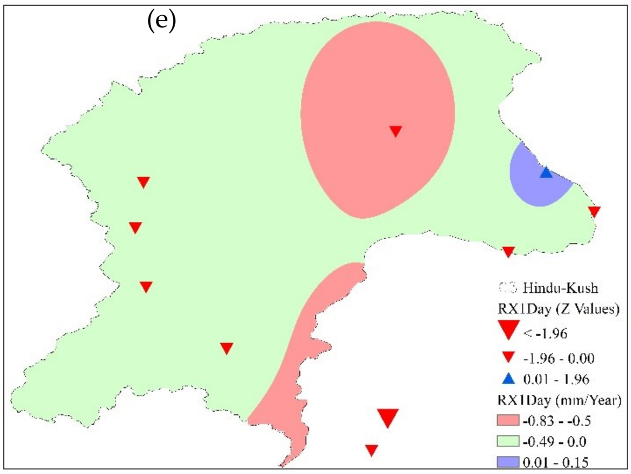


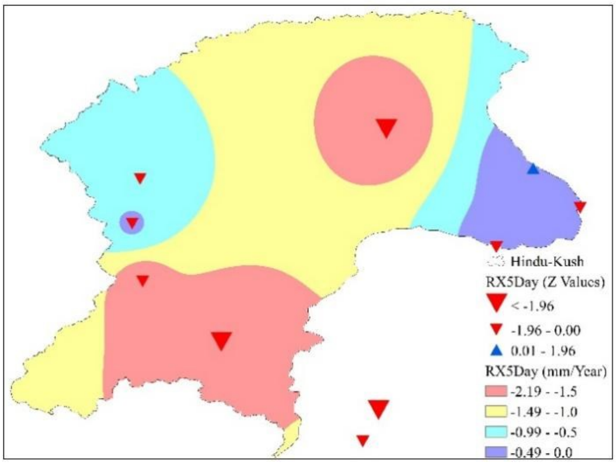
(d)


Hindu-Kush
R99p (Z Values)
< -1.96
-1.96 - 0.00
0.01 - 1.96
R99p (mm/Year)
-1.6 - -1.0
-0.9 - 0.0

(e)

(f)


Hindu-Kush
RX1Day (Z Values)
< -1.96
-1.96 - 0.00
0.01 - 1.96
RX1Day (mm/Year)
-0.83 - -0.5
-0.49 - 0.0
0.01 - 0.15


Hindu-Kush
RX5Day (Z Values)
< -1.96
-1.96 - 0.00
0.01 - 1.96
RX5Day (mm/Year)
-2.19 - -1.5
-1.49 - -1.0
-0.99 - -0.5
-0.49 - 0.0

(g) (h)

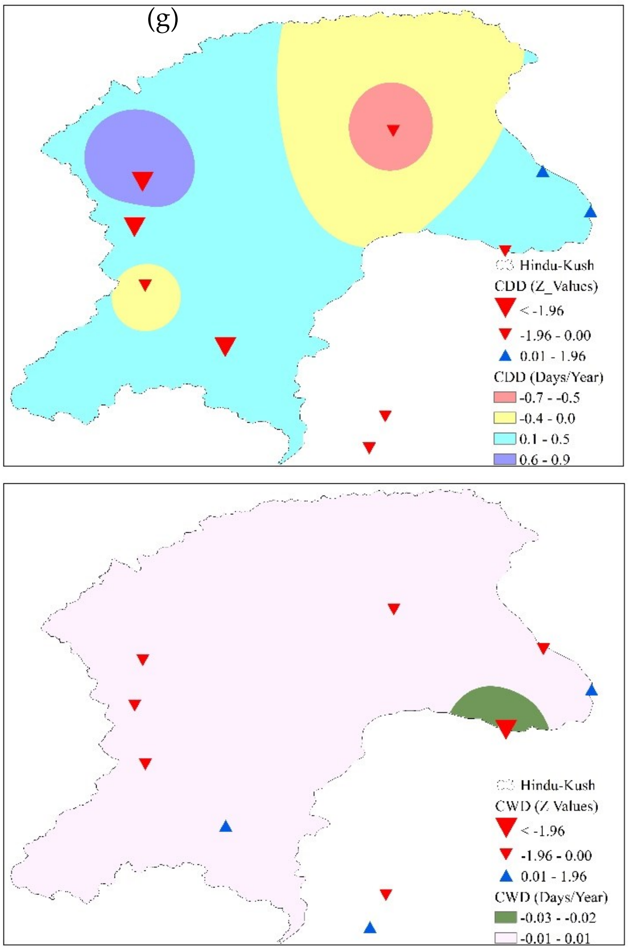


Figure 5. Spatial distribution maps of the rates of changes (during 1990-2020) in the extreme precipitation indices in the Hindu-Kush Mountains of Pakistan.

Across the whole study domain, three stations demonstrated significantly declining trends in total annual precipitation, while the majority of stations indicated a decreasing tendency (Figure 5a). The annual count of heavy precipitation days (with daily precipitation more than 25 mm) was decreased at nine out of ten weather stations (Figure 5b), among them four stations showed statistically significant decreasing trend. Similarly, all of the other indices showed decreasing trends over majority of the weather stations in the Hindu-Kush Mountains of Pakistan. Although some stations showed increasing tendency of CWD, CDD, RX5Days, andRX1Days precipitation indices in the study domain, none of the stations experienced significant increase in these indices over the past three decades. It was obvious that the statistically significant decreasing trends were mostly observed in the southern parts of the mountain. Generally, all indices showed a decreasing trend direction from the northeast side to the south-west direction.

. Conclusions

On the basis of computed results, following conclusions were drawn:

The amount of total annual precipitation over the Hindu-Kush Mountains were decreased significantly over the period of past three decades. The decreasing rate (-5.31 mm/year) was statistically significant at 95% confidence level.

The annual count of consecutive dry days was slightly increased over the past three decades in the study domain, although the increasing trend was not statistically significant.

The majority of stations experienced a decline in the frequency of annual counts of consecutive wet days.

The majority of the indices that were taken into consideration indicated a downward trend moving from the northeast to the southwest.

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