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Analyzing the Spatiotemporal Changes in Climatic Extremes in Cold and Mountainous Environment: Insights from the Himalayan Mountains of Pakistan

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Abstract: This study assessed the past changes in extreme precipitation and temperature events across the Himalayan Mountains of Pakistan. This cold and mountainous environmental region has witnessed a significant increase in climate-related disasters over the past few decades. Spatiotemporal changes in extreme temperature and precipitation events were analyzed using 24 indices developed by the Expert Team on Climate Change Detection and Indices (ETCCDI). For this study, in situ data of 16 national meteorological stations were obtained from the Pakistan Meteorological Department (PMD) for the past three decades (1991–2020). The significance of the trends was assessed using the modified Mann–Kendall (MMK) test, and the Theil–Sen (TS) slope estimator was used to estimate the slope of the trend. The results showed that there has been a consistent decline in the total precipitation amount across the Himalayan Mountains of Pakistan. The trend exhibited a decrease in the annual average precipitation at a rate of −6.56 mm/year. Simultaneously, there was an increasing trend in the annual average minimum and maximum temperatures at rates of 0.02 °C/year and 0.07 °C/year, respectively. The frequencies of consecutive wet days (CWDs) and maximum 5-day precipitation (RX5day) have decreased significantly, with decreasing rates of −0.40 days/year and −1.18 mm/year, respectively. The amount of precipitation during very wet days (R95p) and extremely wet days was decreased by −19.20 and −13.60 mm/decade, respectively. The warm spell duration (WSDI) and the frequency of warm days (TX90p) across the Himalayan Range both increased by 1.5 and 1.4 days/decade. The number of cold days (TX10p) and cold nights (TN10p) decreased by 2.9 and 3.4 days/decade. The average temperature of the hottest nights (TXn) and the diurnal temperature range (DTR) were increased by 0.10 and 0.30 °C/decade. The results indicated an increasing tendency of dry and warm weather in the Himalayan region of Pakistan, which could have adverse consequences for water resources, agriculture, and disaster management in the country. Therefore, it is essential to prioritize the implementation of localized adaptation techniques in order to enhance sustainable climate resilience and effectively address the emerging climate challenges faced by these mountainous regions.

Keywords: climate change; spatiotemporal changes; extreme temperature and precipitation indices; modified Mann–Kendall test; Himalayan Mountains

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1. Introduction

The Hindu Kush, Karakoram, and Himalayan (HKH) region, which spans over 4.3 million km^2, encompasses parts of Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan [1]. This region is characterized by its vast mountainous landscape and hosts some of the highest peaks on earth, making it one of the most unique mountain systems worldwide [2]. The mountains in the HKH region play a critical role in the water supply of Asia [3]. With many high-altitude areas storing water as snow and glaciers, there are intricate changes in the hydroclimate of the region. Additionally, the HKH region is the source of ten major river basins, including the Amudarya, Brahmaputra, Ganges, Indus, Irrawaddy, Mekong, Salween, Tarim, Yangtze, and Yellow Rivers.

Considerable changes are occurring in the climate system of HKH mountains, primarily due to human activities [4,5]. The effects of climate change are posing serious threats to economic stability, food security, human health, and ecosystems of this region. It is well documented that climate change would increase the frequency and severity of extreme weather events, such as droughts, heat waves, and heavy rainfall in many parts of the world [5–8]. The changing behavior of climate and its extremes are already impacting various sectors such as agriculture, infrastructure, water resources, hydropower, and ecosystems [9].

In this era of climate change, comprehensive regional and global assessments of the changes in spatiotemporal patterns of extreme climatic events are essential [10,11]. Such assessments of climatic extremes can be accomplished using certain standardized indicators, as they can provide detailed information about different levels of extreme events. Using the standardized indices, researchers and managers can make more detailed evaluations of the hazards associated with extreme events. The Expert Team on Climate Change Detection and Indices (ETCCDI) has established a collection of standardized indices to evaluate extreme climatic occurrences [12]. These indices have been extensively utilized in various regional and global studies. The World Meteorological Organization (WMO) has also recommended the use of these standardized indices for the comparison of the changing patterns of climatic extremes in different regions.

Numerous studies have used the ETCCDI indices to evaluate climate extremes [13–16]. According to the reviewed literature, many parts of the world are experiencing increased intensity and frequency of heavy precipitation events [17]. Some recent assessments have indicated the increasing tendencies of extreme precipitation events in Europe [18], Central Asia [19], South Asia [20], the Middle East [21], and the Tibetan Plateau [22]. In recent decades, there has been a noticeable rise in the frequency of heavy rainfall events across mainland China [23]. Over the past three decades, there has been a significant increase in intense precipitation events in Bangladesh [10]. Conversely, the frequency of extreme precipitation events has decreased in most parts of Pakistan, as revealed by several previous assessments in the entire country and across the upper Indus Basin [12]. Annual average temperature and summer precipitation are increasing across the country; conversely, annual average precipitation is decreasing [13]. Spies [14] documented a decreasing trend of snowfall and summer precipitation over the Karakoram Mountains of Pakistan. In the Himalayan range, Mahmood et al. [15] found a significant increase in the future average annual temperature. They also found an increasing trend of spring and summer precipitation, with a decreasing tendency of winter and total annual precipitation. Increasing temperatures and decreasing snow cover are significantly affecting the hydrological regimes of the Himalayan rivers, as highlighted by Azmat et al. [24]. Furthermore, it is expected that the Himalayan region will become warmer and wetter by the end of this century [25]. Over the past thirty years, there has been a decrease in both the average annual precipitation and various extreme precipitation indices in the Pakistani subtropical highlands [12]. These changes pose significant challenges for better management of water resources and agricultural practices.

Pakistan encompasses three distinct mountainous ranges—the Hindu Kush, Karakoram, and Himalayas (HKH)—as shown in Figure 1 (shaded), each with unique climatic conditions, terrain, glacial extents, ecosystems, and orientations [16]. Most of the previous investigations of climate change have overlooked the geographical boundaries of these mountains in the country. Therefore, a clear understanding of the changing patterns of extreme precipitation and temperature events is lacking, particularly in the Himalayan mountains of Pakistan. Assessments of past precipitation and temperature extremes on the regional levels are important for preparing sustainable climate resilience policies [26]. The recent intense precipitation and extreme temperature events in the mountainous regions of South Asia highlighted the need for comprehensive assessments using longer in situ records [27]. This is particularly important for the mountains in Pakistan. These mountains, which play a crucial role as a climatic and hydrological regulator in Asia, are susceptible to the cumulative consequences of climate extremes [28]. The region is facing a growing threat to its water resources, infrastructure, food security, and regional economic development due to the increasing intensity of extreme temperature events caused by climate change [5]. In the Karakoram mountains, rising winter temperatures, evidenced by significant increases in seasonal minimums, are accelerating the melting of the glaciers [29]. There is an increasing trend of intensified and more frequent extreme precipitation events in different parts of the Hindu Kush Mountain [10,30–32]. Some areas, including the northern and southwestern parts of the Himalayas, have experienced a slight decline in extreme precipitation occurrences [33,34].

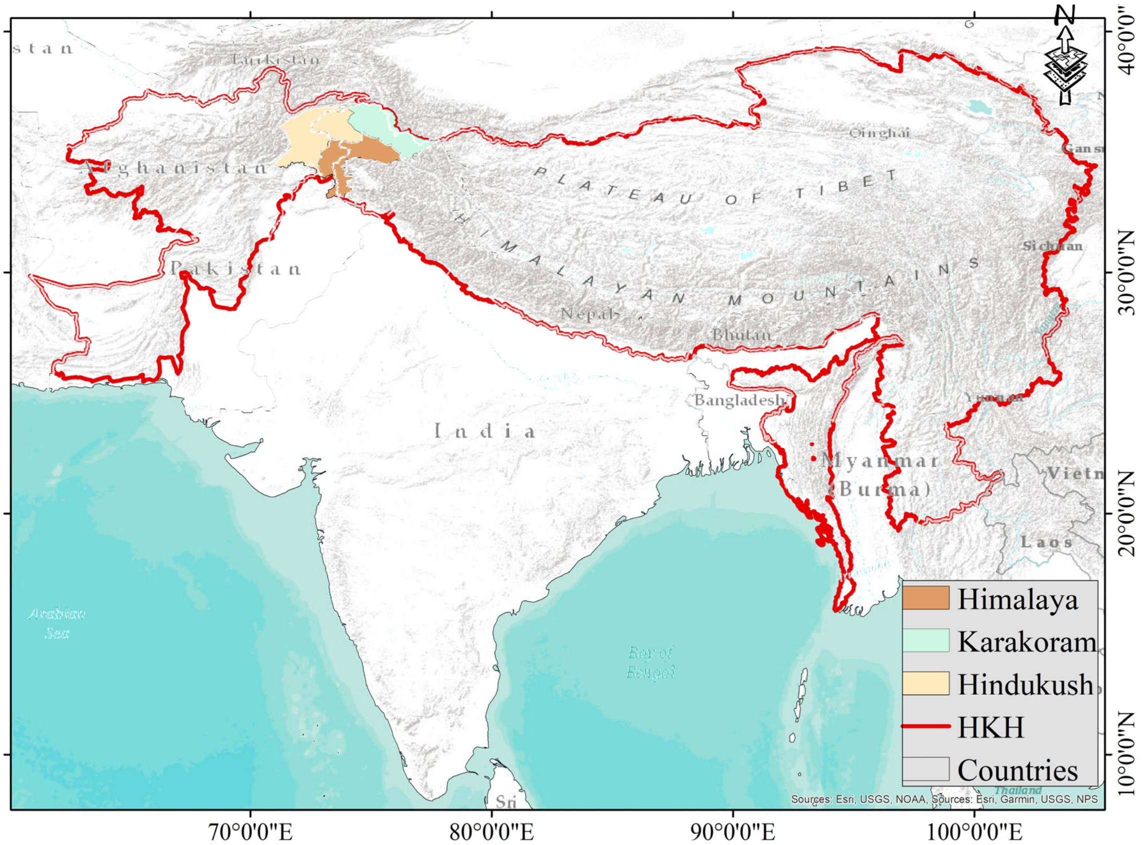

Figure 1. The geographical location of the Hindu Kush, Karakoram, and Himalayan (HKH) region, along with the three subregions (shaded) in Pakistan.

Although all of the presented studies have documented the changes in precipitation and temperature patterns in the northern parts of Pakistan, almost none of them have analyzed the spatiotemporal trends of extreme climatic events in the cold and mountainous environment of the Himalayan range of the country. The objective of this study is to examine the spatial and temporal shifts in the trends of precipitation and temperature indices in the Himalayan Mountains of Pakistan (HMP) from 1991 to 2020, utilizing the indices proposed by ETCCDI and from in situ data. The study specifically aims to (1) identify the temporal trends of these indices over the study period; (2) examine the spatial changes in precipitation and temperature indices over the HMP; and (3) indicate climate-affected areas, particularly those susceptible to heatwaves and droughts, for long-term socioeconomic and agricultural planning. The results of this study will provide insight into how climate extremes are changing in the HMP, which may help decision-makers regarding risk management and climate change adaptation in the area. The findings of this study are expected to establish a foundation for subsequent research on the region's response to global warming.

2. Materials and Methodology

2.1. Study Region and Datasets

In this study, the Himalayan domain in Pakistan was considered. This range is currently facing numerous challenges. The impact of climate change is causing accelerated melting of the glaciers in this region, surpassing the previously recorded rates [35,36]. Several studies have documented the accelerated warming of the Himalayas. This poses a significant threat to freshwater availability, a crucial resource for millions of people in Asia. The 2nd largest reservoir of Pakistan (Mangla Dam Reservoir) is also located at the foothills of this region, which was also a motivation for the selection of this study region.

In this study, we have assessed the trends of precipitation and temperature extremes in the Himalayan Mountains. Considering the data availability, the spatial extent of the mountains located in the administrative boundary of Pakistan was considered. Figure 2 displays the geographical location and topographical features of the study domain. The topographical map of the study areas was developed using the latest version (Version-3) of the Global Digital Elevation Model (GDEM) of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Previously, Chintalapudi et al. [37] have successfully used this GDEM for hydrological modeling in Guadalupe River basin, Texas, United States. The spatial resolution of the considered GDEM was 30 m. It is situated in South Asia, between 33° and 36° north latitude and 72.5° and 76.5° east longitude. Its topography is characterized as hilly terrain with many peaks exceeding 7000 m, including K2, the second-highest peak on Earth. The elevation within the considered domain ranges from 283 m to 8100 m. In this spatial domain of the mountain, the yearly average precipitation ranges from 160 mm to 1700 mm, while the average annual temperature fluctuates between 10 °C and 24 °C. The spatial distributions of annual average precipitation and temperature, as per observations of the past 30 years, are shown in Figure 3. This range displays considerable variations in the land use/ land cover due to the distinct topography and climatic conditions. The land use/land cover (LULC) map of the study area (for 2023) is shown in Figure 2b. Over the higher altitudes, the landscape changes to alpine pastures and desolate terrain, which may be covered with perennial ice or exposed rock formations. This range is the source region of several tributaries of the Indus River, including Jhelum, Neelam, Astore, and Chenab, which are crucial for sustainable hydropower and food production in Pakistan.

For the analysis of spatiotemporal dynamics of extreme precipitation and temperature events over the past three decades (from 1991 to 2020), the daily observations of both variables were attained from the Pakistan Meteorological Department (PMD) and the Water and Power Development Authority (WAPDA) of the country. The observations of 24 automatic weather stations were acquired from these organizations. Previously, we have assessed the performances of several reanalysis- and satellite-based climatic datasets for this study domain; however, no suitable product was identified. Therefore, only in situ datasets were considered for this assessment [38–40]. The study follows specific guidelines to ensure data completeness, as recommended by [41]. Monthly datasets are regarded as reliable if they have at most five missing daily observations. Similarly, yearly datasets are considered suitable if all months meet the criterion mentioned earlier. Lastly, a station's observations are useable if it has less than five missing years over its entire observation period. Based on this criterion, the data of only 16 stations were finalized for this assessment. The quality of the climate data was assured by both organizations (i.e., PMD and WAPDA).

This study employed the linear interpolation method for (one-day) gap filling in daily climatic observations. The areal average values of climatic variables were obtained using the Thiessen Polygon method, which was recommended by previous studies [42,43]. The details of 16 considered weather stations are provided in Table 1.

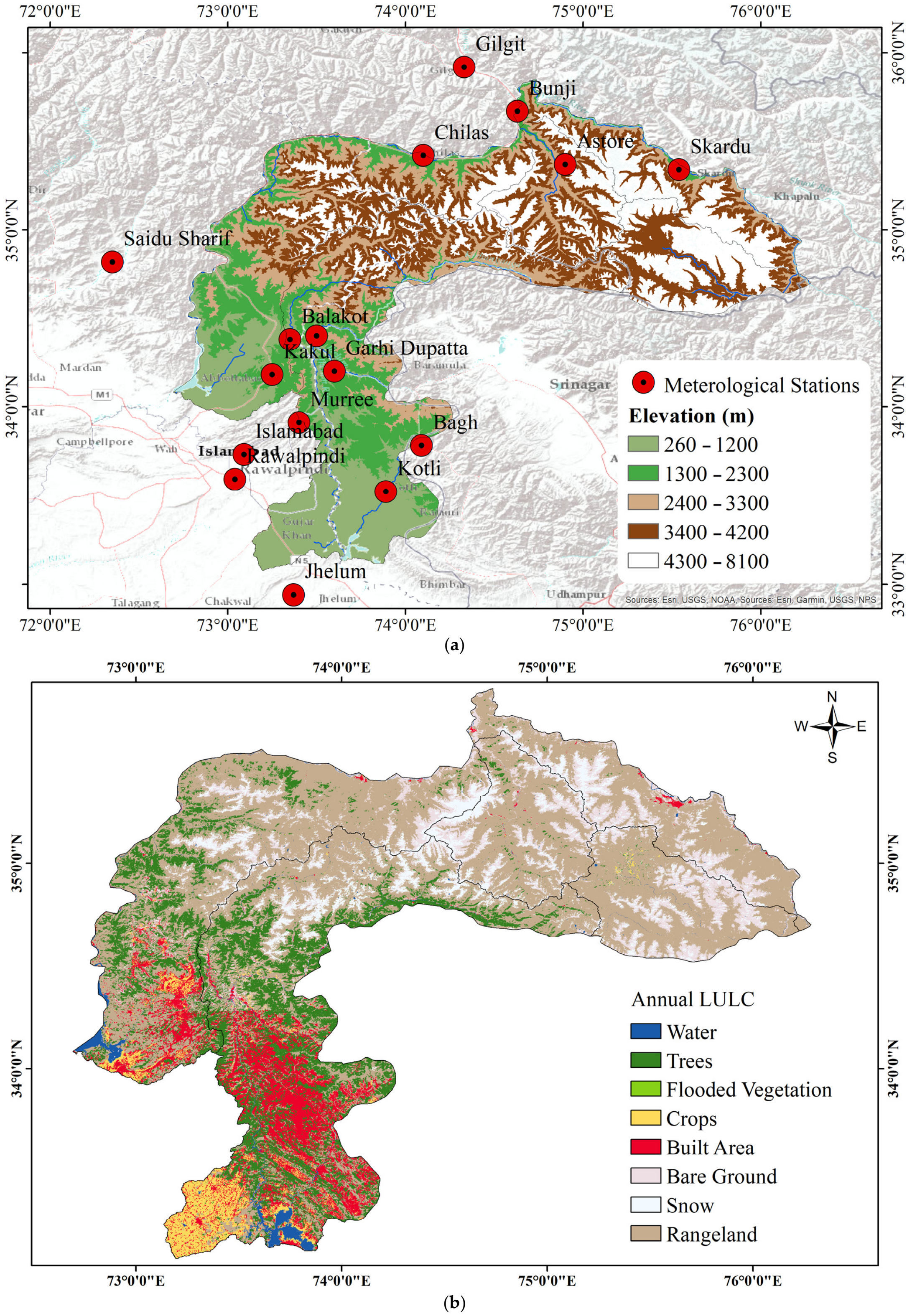

Figure 2. (**a**) Topographic map of the Himalayan Mountain of Pakistan. (**b**) Land use/land cover (LULC) map of the study area.

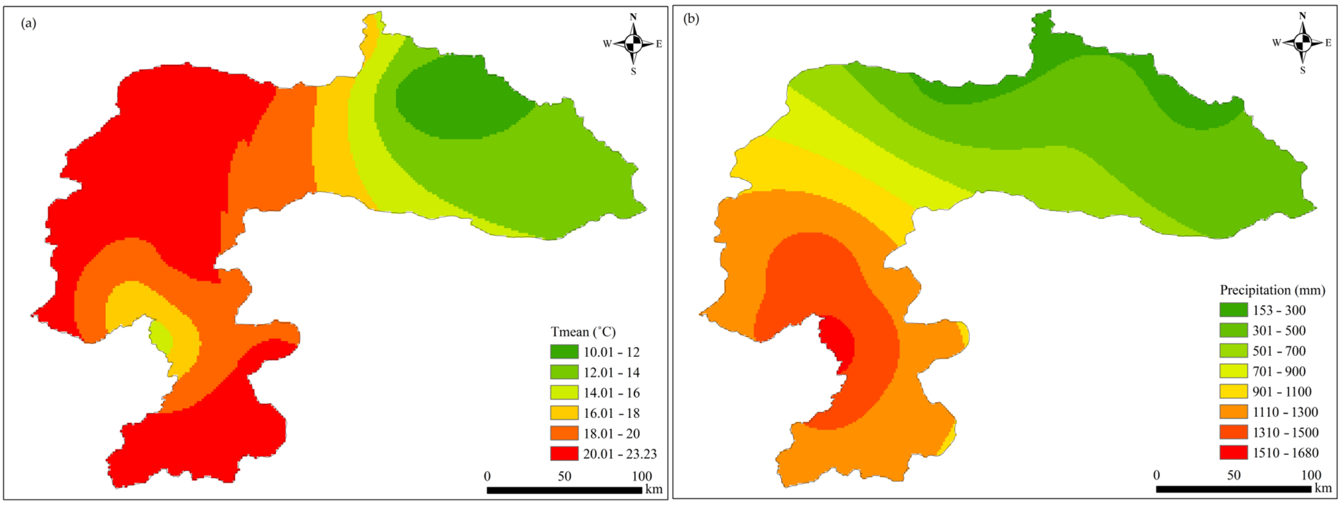

Figure 3. Maps depicting the spatial distributions of (**a**) annual average temperatures (°C) and (**b**) annual average precipitation (mm) across the Himalayan range in Pakistan.

Table 1. Information of the location, elevation, average annual precipitation and temperature of the selected weather stations.

Sr. No.	Index No.	Weather Station	Long. (dd)	Lat. (dd)	Elevation (m)	Temperature (°C)	Precipitation (mm)
1	41520	Astore	74.91	35.36	2170	10.10	459.71
2	Nill	Bagh	74.10	33.79	2200	20.70	1165.59
3	41536	Balakot	73.36	34.38	996	18.80	1475.03
4	41518	Bunji	74.63	35.67	1470	17.70	160.73
5	41519	Chilas	74.10	35.42	1251	20.40	196.82
6	43533	Garhi Dupatta	73.60	34.20	814	19.70	1338.98
7	41516	Gilgit	74.33	35.92	1460	16.00	145.60
8	Nill	Islamabad	73.09	33.73	569	21.80	1262.51
9	41598	Jhelum	73.37	32.94	287	23.90	862.13
10	41535	Kakul	73.25	34.18	1309	16.90	1312.16
11	43563	Kotli	73.89	33.52	614	21.90	1183.75
12	Nill	Murree	73.40	33.91	2127	13.40	1694.61
13	43532	Muzaffarabad	73.50	34.40	838	20.50	1377.73
14	Nill	Rawalpindi	73.05	33.58	540	21.70	1248.58
15	41523	Saidu-Sharif	72.36	34.81	970	26.30	1036.64
16	41517	Skardu	75.55	35.35	2317	11.90	228.13

2.2. Precipitation and Temperature Indices

The past changes in extreme weather events were assessed using already-established indices of ETCCDI. These indices can be classified into three groups: percentile-based, absolute, and duration-based. The definitions and more details about the indices can be obtained from a recent study [44]. The names and classifications of the considered indices are presented in Table 2. In this study, ten precipitation indices and twelve temperature indices were computed for every station. The analysis of these indices was performed in the RClimDex 1.0 software. Other than PRCPTOT, all of the indices were classified into three different groups, as shown in Table 2. The two percentile-based indices, R95p and R99p, representing very wet and extremely wet days, were determined using the bootstrapping method.

Table 2. Names and classification of climate indices into percentile-based, absolute, and duration-based categories for precipitation and temperature measurements.

Sr. No.	Category	Precipitation Indices	Temperature Indices
1	Percentile-based indices (precipitation indices in mm and temperature indices in days)	R95p R99p	TN10p TN90p TX10p TX90p
2	Absolute indices (precipitation indices in mm and temperature indices in °C)	R10 R20 R25 RX1day RX5day	TNn TNx TXn TXx TXmean TNmean
3	Duration-based indices (both indices in days)	CDD CWDs	CSDI WSDI

2.3. Analysis of Extreme Precipitation and Temperature Trends

In this study, the significance of the trends in the extreme precipitation and temperature indices were assessed using the modified Mann–Kendall (MMK) test, which was introduced by Hamed and Rao [45]. This method is a non-parametric statistical approach, representing an updated version of the original Mann–Kendall test that takes into account serial correlations and seasonal effects. This method is great for handling missing or incomplete data because it does not require parameter estimation. Both short-term and long-term datasets can be used with confidence by applying this test, which is a reliable and flexible method for trend analysis.

In order to determine the trend's significance, the MMK test statistics were compared to their predicted values under the null hypothesis of no trend. The variance ($V(S)$) and corrected variance ($V^*(S)$) of the MMK test were determined considering the following equations:

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

$$sgn\left(x_k - x_j\right) = \begin{Bmatrix} 1 & if\ x_k - x_j > 0 \\ 0 & if\ x_k - x_j = 0 \\ -1 & if\ x_k - x_j < 0 \end{Bmatrix} \tag{2}$$

$$V(S) = \left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)/18\right] \tag{3}$$

$$V \times (S) = V(S)Cor \tag{4}$$

where

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

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

where n shows the total number of values in time-series data, x_j and x_k indicate the jth and kth values in the data, the time duration of the data series is represented by t, and the significant autocorrelation function of the ranked values is indicated by s(i). If the calculated value of test statistics (Z) is positive (negative), then the trend is increasing (decreasing). In this investigation, the significance of the estimated trends was assessed at the 95% significance level.

To determine the slope of the identified trends, the Theil–Sen (TS) method was applied. This provides reliable estimates of the magnitude and direction of trends.

$$T_i = \frac{x_j - x_k}{j - k} \quad (7)$$

$$\mathrm{Q_i} = \begin{Bmatrix} \mathrm{T}_{\frac{N+1}{2}} & \text{N is odd} \\ \frac{1}{2}\left(\mathrm{T}_{\frac{N}{2}} + \mathrm{T}_{\frac{N+2}{2}}\right) & \text{N is even} \end{Bmatrix} \quad (8)$$

The MMK and TS slope estimator provided a statistically robust framework for analyzing trends in precipitation and temperature extremes. These methods are particularly useful when dealing with data distributions that do not follow a normal distribution, trends that are not linear, or incomplete datasets. With reliable insights into these key climatic variables, we can better understand trends and changes in them. This study evaluated the significance of the trends at a 95% confidence level. A Z-value close to 0 means no significant trend, while values beyond ±1.96 indicate a significant trend with a 95% confidence level.

2.4. Spatial Interpolation

It is well documented that non-geostatistical spatial interpolation techniques may result in inconsistencies in mountainous areas. This is because there are a number of systematic mistakes, uncertainties related to weather station density, and interpolation procedures [46]. Several studies have assessed the efficacy of different spatial interpolation techniques for climatic variables in different mountainous regions [47,48]. The effectiveness of spatial interpolation techniques is primarily determined by the chosen algorithm, the characteristics of regional terrain configuration, and the distribution of weather stations. Li and Heap [47] compared 32 spatial interpolation techniques and concluded that the Kriging method outperforms all non-geostatistical techniques. Therefore, this study used the Kriging method for interpolating annual average temperature, precipitation, and the outcomes of the MMK test.

3. Results

Previous studies have reported considerable changes in the climate system of the Himalayan region of Pakistan [24,49,50], critical for regional adaptation strategies. Considering the findings of these studies, the impact of climate change on the spatiotemporal changes in the patterns of extreme precipitation and temperature events was assessed over the past three decades (1991–2020).

3.1. Extreme Precipitation Trends

Trends in the areal average values of ten precipitation indices were assessed for the past three decades (1991–2020). Temporal trends of all precipitation indices are displayed in Figure 4. Analysis of the total amount of annual average precipitation (PRCPTOT) revealed a decreasing trend (at a rate of −6.56 mm/year) in the Himalayan Mountains of Pakistan, as indicated by the linear trend in Figure 4a. It was found that the number of "consecutive dry days (CDDs)" increased (at a rate of 0.33 days/year), whereas all other extreme precipitation events decreased over the past three decades. The number of "consecutive wet days (CWDs)" and the "maximum five days of precipitation (RX5day)" were significantly decreased (at rates of −0.40 and −1.18 mm/year, respectively). The number of heavy precipitation days (R10), very heavy precipitation days (R20), and precipitation days with intensity of more than 25 mm/day decreased at rates of −0.16 mm/year, −0.04 mm/year, and −0.07 mm/year, respectively. The trends of 95th percentile and 99th percentile precipitation indices also decreased at rates of −1.92 and –1.36 mm/year, respectively. The amount of maximum one-day precipitation also decreased at a rate of −0.37 mm/year.

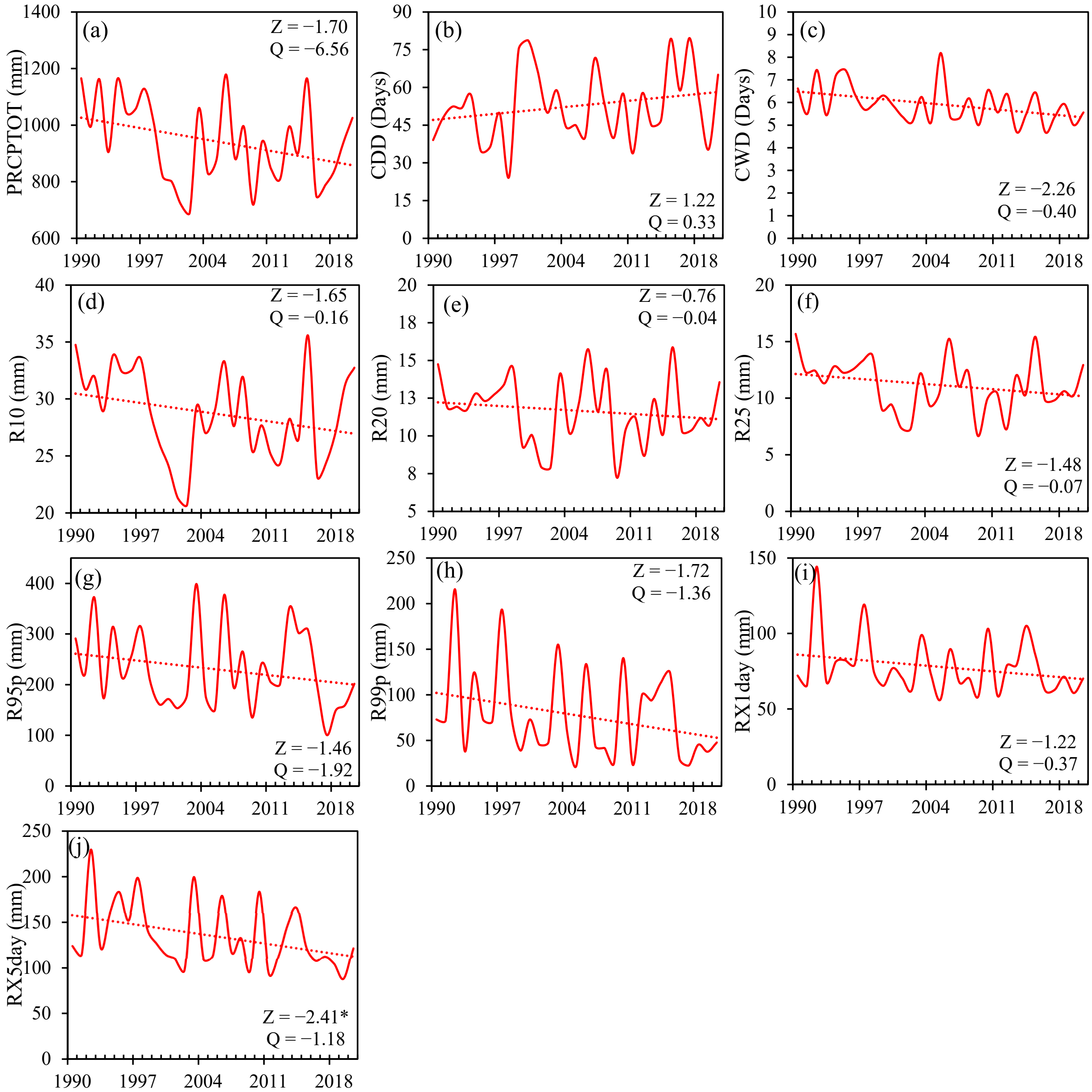

Figure 4. Linear trends of precipitation indices including (**a**) PRCPTOT, (**b**) CDD, (**c**) CWD, (**d**) R10, (**e**) R20, (**f**) R25, (**g**) R95p, (**h**) R99p, (**i**) RX1day, and (**j**) Rx5day in the Himalayan Mountains of Pakistan. In these graphs, Z represents the MMK test statistics and Q denotes the slope of the trend. The symbol * shows the statistically significant value at a 95% confidence level.

Spatial distributions of the MMK test results for the duration-based precipitation indices are shown in Figure 5. In this figure, stations with Z values greater than 1.96 indicate a statistically significant increasing trend, whereas stations with Z values less than −1.96 demonstrate a statistically significant decreasing trend at the 95% confidence level. Considerable variations in the spatial patterns of CDDs and CWDs were observed across the Himalayan Mountains. The spatial variability map of the CDD revealed that the consecutive dry days increased in the majority of the locations. The increasing trend of CDDs was statistically significant at the Astore station (increasing at a rate of 1.10 days/year). Two stations showed a decline in CDDs. The rate of change in the CDD trend ranges from −0.01 days/year to 1.10 days/year. On the other hand, the majority of the stations exhibited a decline in consecutive wet days. This declining trend was significant at three specific stations: Chilas, Muzaffarabad, and Skardu. In this study area, the number of wet days increased at only three stations: Bunji, Saidu Sharif, and Kakul. The rate of change for CWDs ranges from −0.11 days/year to 0.01 days/year. Table 3 displays the slope of the trend for CDDs and all other precipitation indices. There is a noticeable distinction between the behavior of extreme precipitation events and the overall trends of yearly precipitation, as seen by the comparisons of the values of PRCPTOT, R95p, and R99p in Table 3. The variations suggest that R95p and R99p, which focus on extreme precipitation events, exhibit greater sensitivity to short-term, intense precipitation events than the PRCPTOT, which averages overall annual precipitation, including both extreme and non-extreme events. The significant positive and negative variations in R95p and R99p, despite stable or slightly declining PRCPTOT, indicate that extreme events are becoming either more variable or intense in specific regions, even as total precipitation trends remain relatively moderate. This distinction between indices offers significant insights. Despite an overall declining trend in precipitation, as indicated by PRCPTOT values, extreme precipitation events (represented by R95p and R99p) may exhibit distinct behavior due to climate variability, resulting in increased intensity or frequency of such extremes. Understanding the behavior of these extremes is essential for planning future water resource management, emergency preparation, and mitigation plans. The observed patterns of consecutive dry and wet days indicate the possibility of a drought, which will have significant impacts on the water resources, hydropower generation, and ecosystem of the region.

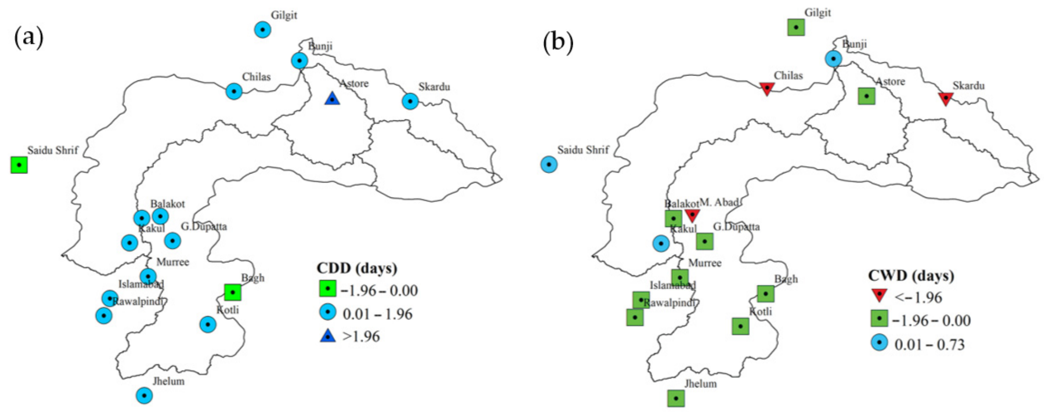

Figure 5. Spatial distribution maps of the MMK test statistics for (**a**) CDD (consecutive dry day duration) and (**b**) CWD (consecutive wet day duration) in the Himalayan Mountains of Pakistan. Stations exhibiting Z values > 1.96 signify a statistically significant increasing trend, while those with Z values < −1.96 reflect a statistically significant decreasing trend at the 95% confidence level.

The results of the MMK test for the three absolute indices (R10, R20, and R25) are presented in Figure 6. The R10 map, representing days with >10 mm of precipitation, exhibited a significantly increasing trend of heavy precipitation at Gilgit station (with Z > 1.96), as shown in Figure 6a. Four stations showed a gradual rise in heavy precipitation events, although this increase was not statistically significant at a 95% significance level. Conversely, 11 stations exhibited a declining trend in this index, with the trend being statistically significant at three stations (Murree, Bagh, and Astore). The range of the R10 trend slope varies from −0.65 days/year to 0.15 days/year. Figure 6b displays the map of R20, revealing a notable reduction in days with precipitation intensity exceeding 20mm/day at Bagh and Islamabad stations. Additionally, six stations exhibited a declining trend in very heavy precipitation events. The results of the MMK test indicated a slight upward trend in R20 at eight stations, although none of these findings were deemed statistically significant. The change rate of the R20 varies between −0.38 days/year and 0.20 days/year. In the case of R25 trends, four stations (Astore, Saidu Sharif, Murree, and Bagh) experienced significant decreases in extreme precipitation events, with precipitation > 25 mm/day, while another five stations showed non-significant decreasing trends (with z-values between −1.96 and 0.0). Over the past three decades, the trend of R25 increased at seven stations, as shown in Figure 6c. The trend of the R25 index varies between −0.38 days/year and 0.13 days/year. These variations in precipitation patterns with different intensities across the region underscore the complexity of climate dynamics and the necessity for localized climate resilience and adaptation strategies.

Table 3. The rate of change in all precipitation indices during the past three decades (1991–2020).

Sr.	Stations	CDD	CWDs	PRCPTOT	R10	R20	R25	R95P	R99P	RX1Day	RX5Day
1	Astore	1.10	0.00	−7.10	−0.25	−0.08	−0.09	−2.69	0.00	−0.32	−1.07
2	Bagh	0.00	−0.05	−19.33	−0.65	−0.38	−0.38	−11.54	0.00	−1.85	−3.61
3	BalaKot	0.12	0.00	−8.93	−0.11	−0.12	−0.14	−9.24	−3.00	−1.89	−2.68
4	Bunji	0.50	0.00	0.00	0.00	0.00	0.00	−0.79	0.00	−0.14	−0.41
5	Chilas	0.24	−0.03	−1.71	−0.08	0.00	0.00	0.00	0.00	0.00	−0.27
6	Garhi Dupatta	0.53	−0.08	−7.34	−0.17	0.00	0.00	−1.61	0.00	−0.33	−1.42
7	Gilgit	0.00	0.01	1.46	0.05	0.00	0.00	0.23	0.01	0.15	0.00
8	Islamabad	0.05	−0.04	1.72	0.10	−0.12	0.00	−2.58	0.00	0.09	−0.35
9	Jhelum	0.26	0.00	−10.69	−0.11	0.05	−0.13	−5.56	0.00	−0.65	−2.34
10	Kakul	0.29	0.00	−3.43	−0.19	−0.17	0.00	−9.24	−1.70	−0.34	−0.63
11	Kotli	0.50	−0.05	2.43	−0.05	0.08	0.00	−4.35	0.00	0.88	0.10
12	M. Abad	0.50	−0.11	0.18	0.15	0.00	0.13	2.17	0.00	0.23	−1.35
13	Murree	0.15	−0.05	−19.63	−0.55	0.20	−0.33	3.13	−6.74	−1.88	−3.27
14	Rawalpindi	0.10	−0.04	1.16	0.06	0.00	0.00	8.67	0.00	0.00	−1.41
15	Saidu Sharif	0.00	0.00	−8.76	−0.25	0.00	−0.21	0.00	0.00	−0.35	−2.19
16	Skardo	1.00	−0.05	−3.14	0.00	0.00	0.00	−2.15	0.00	0.00	0.00

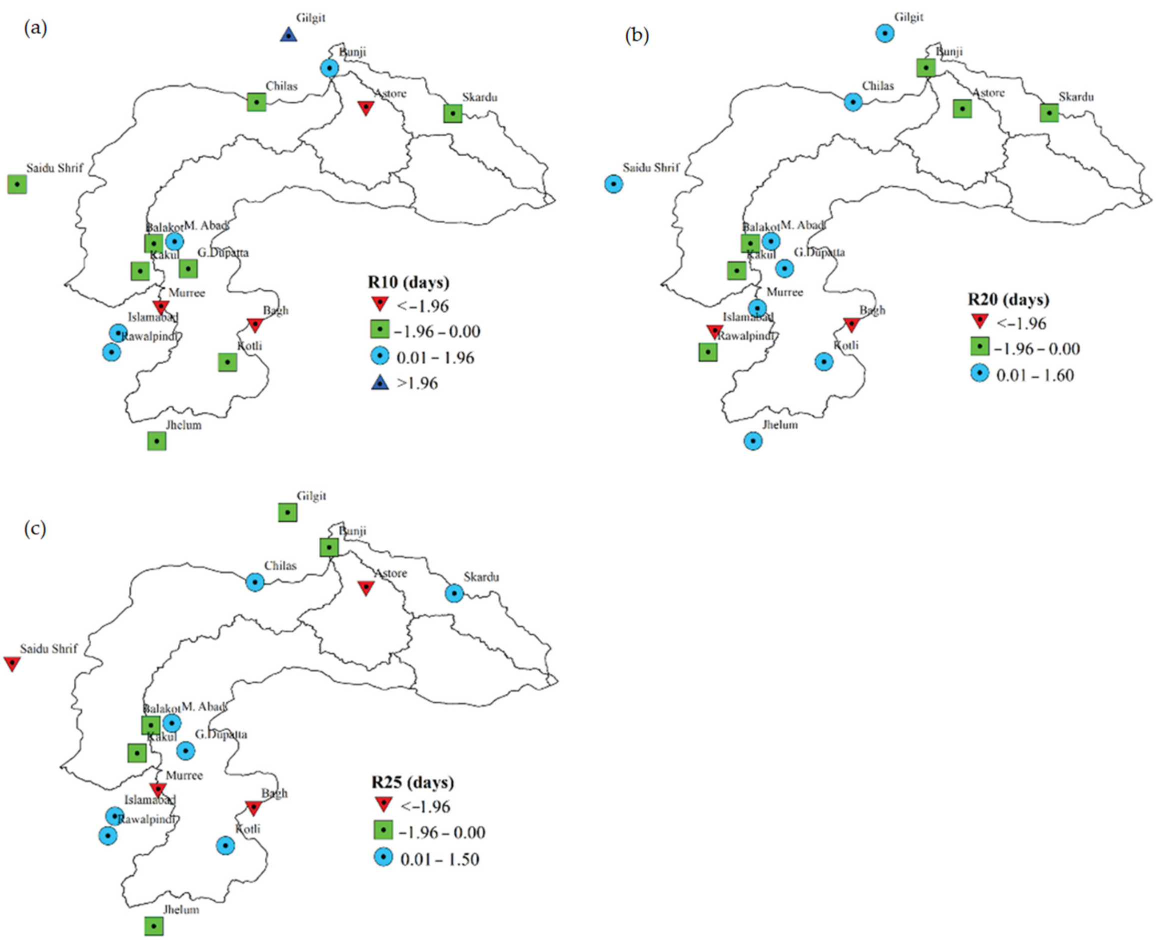

Figure 6. Maps displaying the spatial variations in the results of the MMK test for (**a**) R10, (**b**) R20, and (**c**) R25 across the Himalayan Mountains of Pakistan. Stations exhibiting Z values > 1.96 signify a statistically significant increasing trend, while those with Z values < −1.96 reflect a statistically significant decreasing trend at the 95% confidence level.

Trends of RX1Day ("monthly maximum 1-day precipitation") and RX5Day ("monthly maximum 5-day precipitation") at all considered stations are displayed in Figure 7. It was found that the RX1Day significantly decreased at three stations (Bagh, Balakot, Murree), with Z-values less than −1.96. While nine stations showed a decreasing tendency of this index, only four stations (Gilgit, Kotli, Muzaffarabad, Rawalpindi) showed an increasing potential of RX1Day. The trend rate of RX1Day varies from −1.89 mm/year to 0.88 mm/year. The results of RX5Day showed that only two stations (Gilgit and Kotli) experienced an increasing trend of monthly maximum 5-day precipitation. Five stations (Astore, Bagh, Balakot, Murree, and Saidu-Sharif) exhibited a significantly decreasing trend of this index, with Z < −1.96. Other stations indicated a decreasing tendency of 5-day maximum precipitation in this region. The change rate of RX5day varies between −3.61 and 0.10 mm/year.

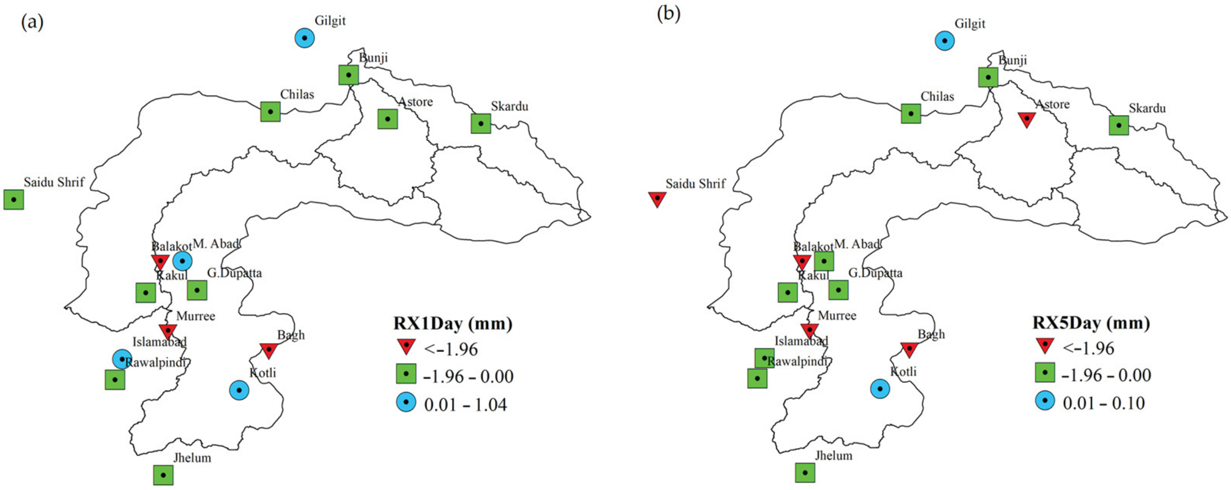

Figure 7. Spatial distributions of MMK test results for (**a**) maximum 1-day precipitation amounts (RX1Day) and (**b**) maximum 5-day consecutive precipitation amounts (RX5Day).

The percentile-based extreme precipitation indices (R95p and R99p) were also estimated to examine the patterns of daily precipitation extremes in the Himalayan range of Pakistan. These indices calculate the annual precipitation total from days when precipitation exceeded the 95th and 99th percentiles of the total precipitation for that day. The results of the MMK test statistics for both of these percentile-based indices are displayed in Figure 8. In most cases, there was a noticeable decline in R95p at the majority of stations, as evidenced by its decrease at 11 stations. The index experienced a significant decrease at three stations (Bagh, Balakot, and Kakol), while the decreasing trend at eight stations was statistically non-significant. Five stations showed a noticeable increase in R95p, with the trend being statistically significant at the Rawalpindi station. The rate of change in R95p ranges from −11.54 mm/year to 8.67 mm/year. The analysis of the R99p index reveals a consistent decline in the 99th percentile of daily precipitation across most stations, as evidenced by Z-values below −1.96. At all other sites, the decreasing trend was non-significant, but at the Murree and Balakot stations, it was statistically significant. Only three stations showed a non-significant increasing trend of R99p. The rate of change in R99p varies between −6.74 and 0.01 mm/year.

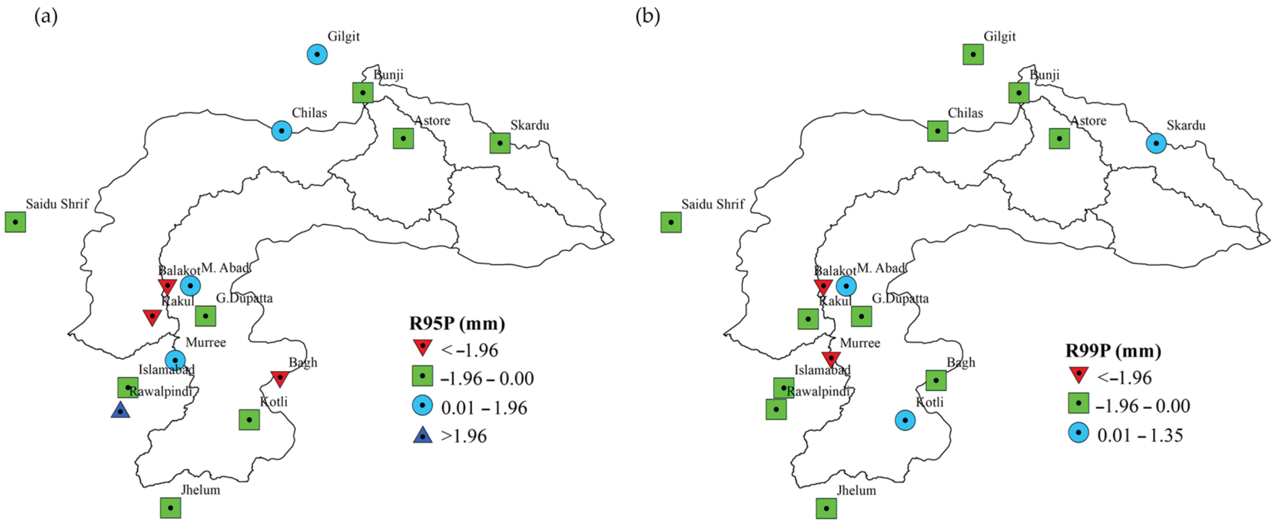

Figure 8. Spatial distribution maps of the MMK test result for (**a**) R95p and (**b**) R99p indices.

3.2. Extreme Temperature Trends

Figure 9 displays the temporal trends of the areal average extreme temperature indices in the Himalayan Mountains of Pakistan. It was revealed that, during the past three decades (1991–2020), both the minimum temperature (TN) and maximum temperature (TX) increased in the studied domain of the Himalayas, with increasing rates of 0.02 and 0.07 °C/year, respectively. Most of the cold indices (including cold spell events (CSDI), cold nights (TN10p), cold days (TX10p), and coldest nights (TNn)) were decreased. The number of cold spells in a year decreased at a rate of −0.14 days/year. The number of warm nights also decreased at a rate of −0.27 days/year, as indicated by the trend of TN90p (Figure 9f). The trend of diurnal temperature range (DTR) increased at a rate of 0.02 °C/year. The TNx (monthly maximum value of daily TN) decreased (Z = −1.87 and Q = −0.07). The annual count of tropical nights (when daily minimum temperature is greater than 20 °C) also exhibited a declining trend in the study domain. The slope of the decreasing trend was −0.41 days/year, as shown in Figure 9i. The trend of TXn (monthly minimum value of daily TX) increased significantly, with an increasing rate of 0.01 °C/year. The trend of annual number of cool days (TX10p) decreased at a rate of −0.29 days/year. However, the annual number of warm days (TX90p) increased (at the rate of 0.14 days/year). The trend of the warm spell duration indicator also increased, a rate of increase of 0.15 days/year.

Figure 10 shows the spatial variations in the trends of the MMK test statistics (Z) and slope (Q) scores for CSDI and WSDI in the selected domain of the Himalayan Mountains. According to the CSDI trend analysis, there was a notable decrease in the total number of cold days across all parts of the mountain. This decrease was statistically significant at three stations (Gilgit, Jhelum, and Kotli), with the southern parts experiencing a higher rate of decrease compared to other areas. The results of other sites are not statistically significant at the 5% significance level. In Figure 10a, the light blue color showed a slight decrease in cold spell days, ranging from −0.29 to 0.00 days/year, whereas the darker blue color showed a more pronounced decrease in cold spell days, between −0.43 and −0.30 days. The trends of the warm spell duration indicator (WSDI) range from—0.26 days/year to 0.56 days/year. A widespread positive trend was observed. The dark-blue shaded area shows a decreasing trend of warm spells (ranges between −0.26 and 0.00 days/year). The light blue areas show a slight increase in the WSDI, ranging from 0.01 to 0.30 days/year. The red regions show significant increase in warm spell days per year, ranging from 0.31 to 0.56 days. The WSDI was significantly increased at one station (Garhi Dupatta).

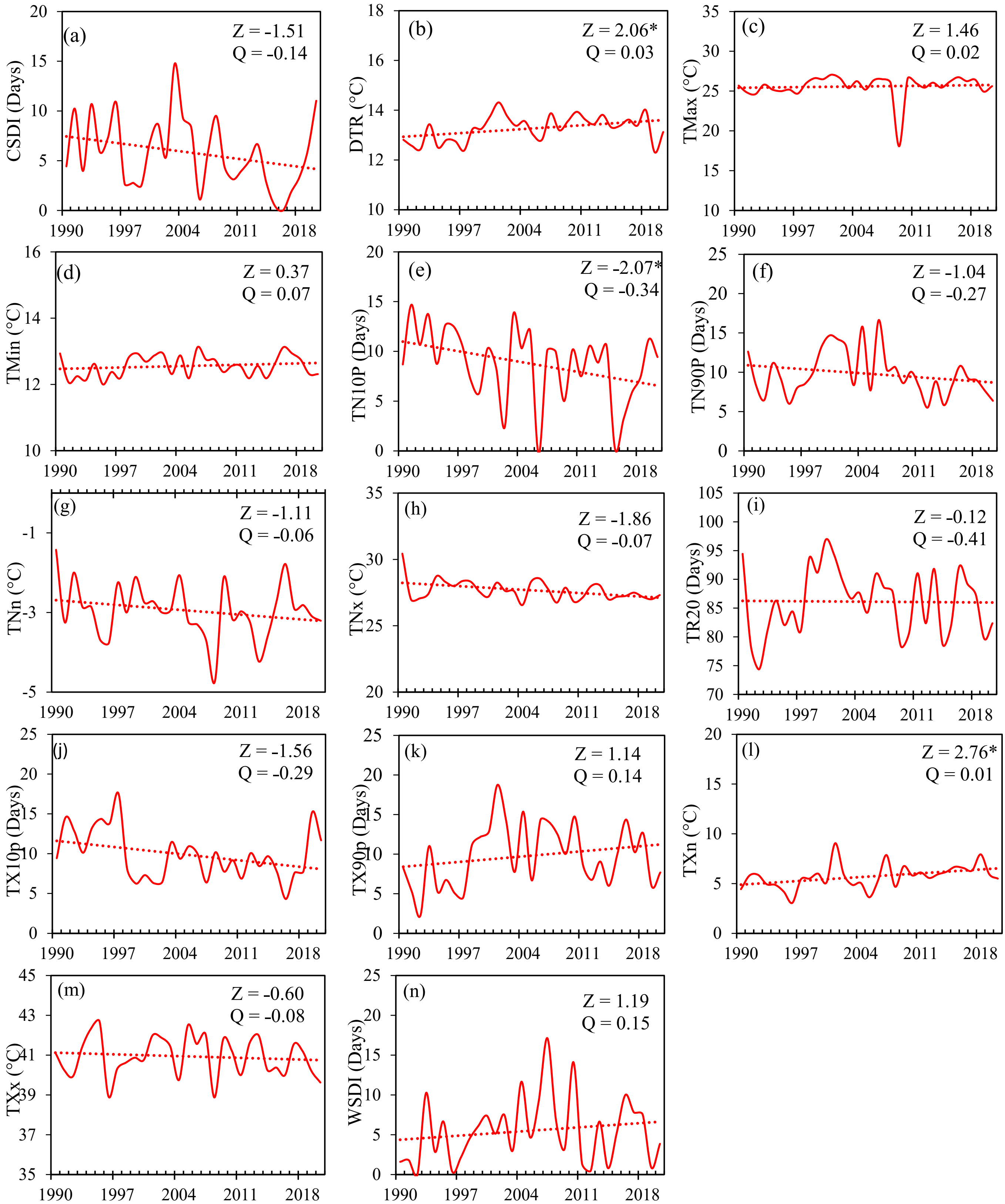

Figure 9. Temporal variabilities of temperature indices (during 1991–2020) in the Himalayan Mountains of Pakistan. In (**a**–**n**), Z signifies the MMK test statistics, while Q indicates the slope of the trend. The symbol * shows the statistically significant value at 95% confidence level.

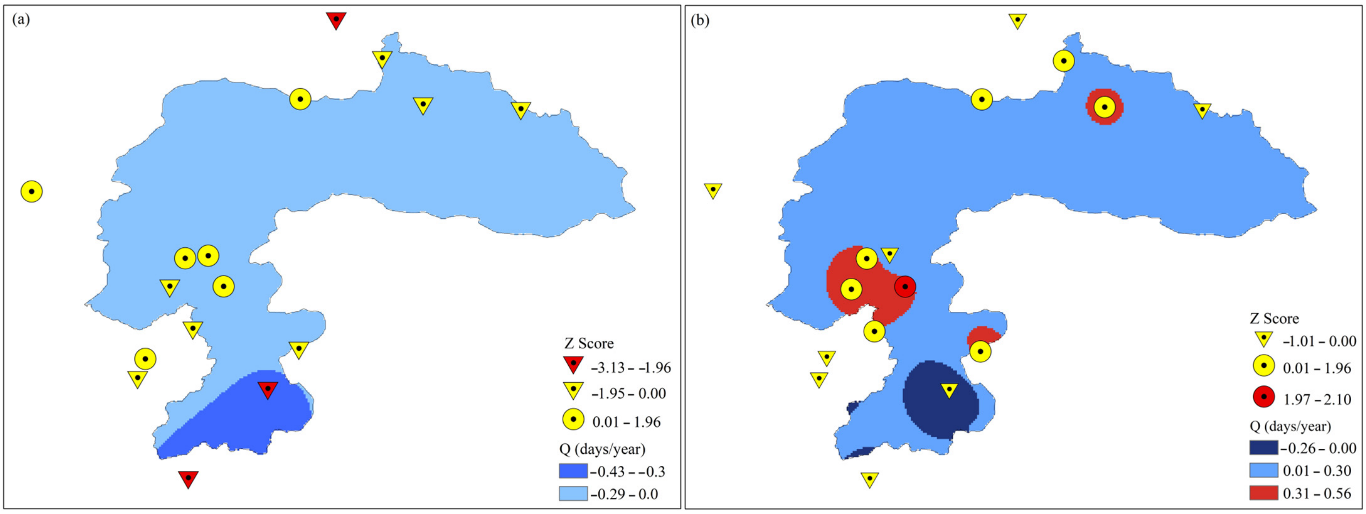

Figure 10. Spatial distribution maps of the MMK test result for (**a**) the cold spell duration index (CSDI) and (**b**) the warm spell duration index (WSDI).

Figure 11 illustrates the spatial variabilities in the trends of percentile-based extreme temperature indices across the Himalayan Mountains of Pakistan. The analysis of trends for the TX10p index reveals a decline in the annual count of cool days in the region, with the rate of decrease ranging from −0.15 to −0.12 days per year. The trend of decrease was statistically significant at seven stations. Figure 11b illustrates the increase in the number of warm days (TX90p) at most locations. The rate of increase ranged from 0.01 to 0.20 days/year. Statistical significance was observed in the increasing trend of warm days at three stations: Balakot, Kakol, and Garhi Dupatta. Analysis of TN10p revealed a consistent decline in cool nights. There was a significant decrease in TN10p at five stations, with the highest rate of decrease being 0.32 days/year. Several stations in different parts of the mountain showed a noticeable trend of cooler nights. Nevertheless, the upward trend did not reach statistical significance at the 95% confidence level (p-value ≤ 0.05). It is worth noting that there has been a decrease in the number of warm nights over the past three decades, as shown by the trend analysis of TN90p (Figure 11d). There was a significant decrease observed at six stations, with a decreasing rate between −0.01 and −0.30 days/year. At other stations, the trend of decreasing was not statistically significant. Some regions in the north and south have seen a slight rise in the frequency of warm days, but this trend was not statistically significant.

The spatial distributions of the Z and Q values for TNn (coldest night), TNx (warmest night), TXn (coldest day), and TXx (warmest day) in the Himalayan region of Pakistan are shown in Figure 12. The analysis of TNn of all stations revealed an overall decreasing trend over the past three decades; the decreasing rate was about −0.06 °C/year. The decreasing trend was statistically significant at the six locations (Bagh, Islamabad, Garhi Dupatta, Muzaffarabad, and Jhelum). Five stations exhibited a marginal, yet statistically insignificant, upward trend. The majority of these positive trends were observed in the northern regions of the mountain. The rate of increase was approximately about 0.05 °C per year. The TNx trend generally decreased at most stations. The trend exhibited a decrease of approximately −0.10 °C/year. The decreasing trend was statistically significant at five stations: Balakot, Bagh, Garhi Dupatta, Kakul, and Muzaffarabad. Five stations showed an increasing trend of TNx; among them, two stations had experienced significant increases in the warmest nights. The overall trend TXn increased in the entire study domain, as indicated by the positive trend of this index at 15 stations. The rate of change in this index varies between 0.01 °C/year and 0.12 °C/year (Figure 12c). Only one station showed a decreasing trend of TXn. The increasing trend was significant at four stations. The rate of change in the TXx varies between −0.06 °C/year and 0.07 °C/year. One station (Buni) showed a statistically increasing trend while two stations (Gilgit and Skardu) indicated a significantly decreasing trend of TXx over the past 30 years. Generally, a decreasing trend of the TXx prevails over most of the locations, the decreasing trend varies between −0.06 and 0.00 °C/year, where the positive trend varies between 0.01 and 0.07 °C/year.

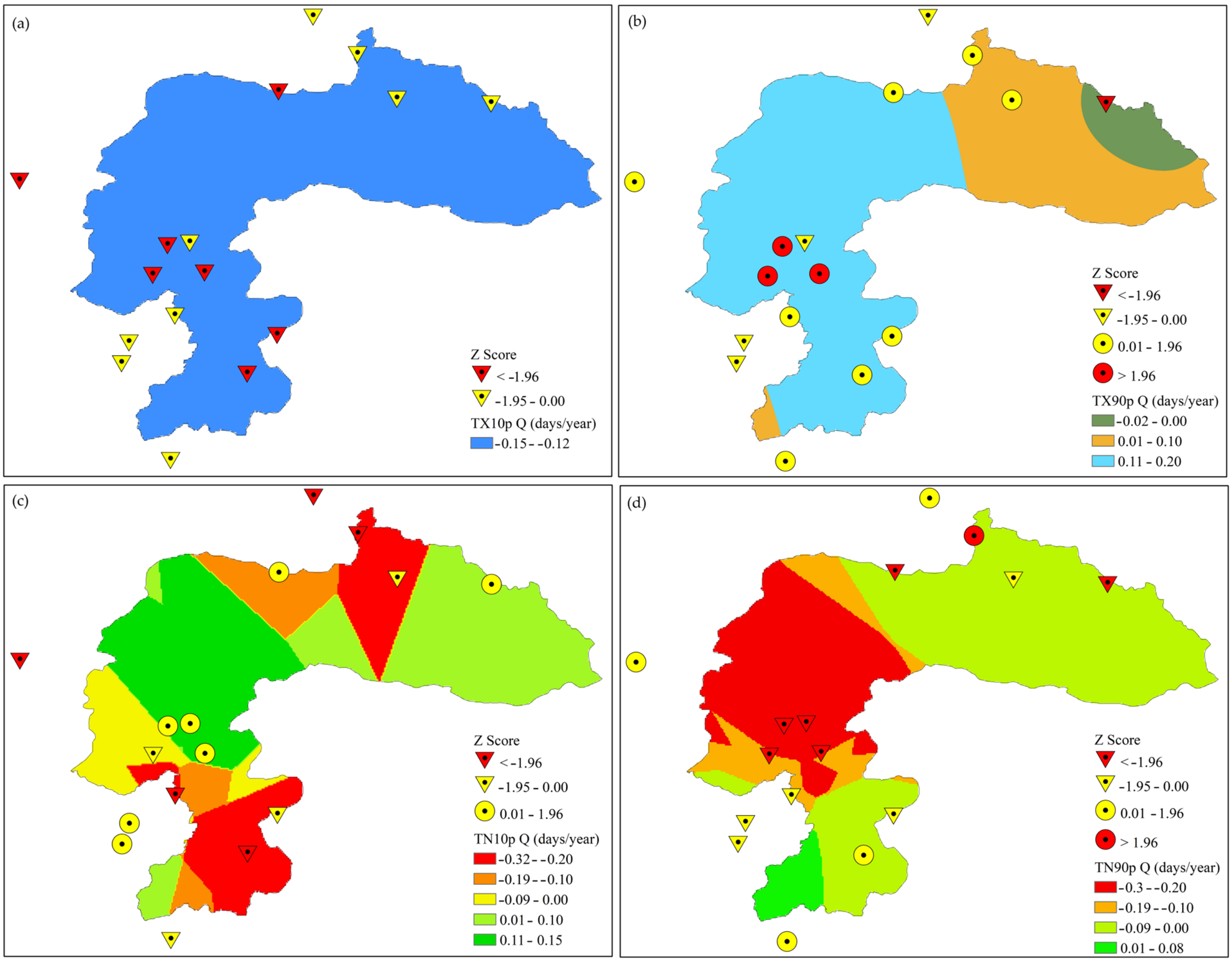

Figure 11. Spatial variations in the Z and Q for (**a**) TX10p, (**b**) TX90p, (**c**) TN10p, and (**d**) TN90p across the study domain.

The overall trend of TXmean increased. The trend showed statistical significance at five stations (Balakot, Chilas, Ghari Dupatta, Kakul, and Kotli), while the trends at all other stations were not significant (Figure 13). The rate of change in TXmean varies between 0.01 °C/year and 0.09 °C/year. The trend analysis of mean minimum temperature (TNmean) across the Himalayan region of Pakistan represents a mix of both increasing and decreasing trends. A total of nine stations showed a decreasing trend of TNmean; among them, three stations showed a statistically significant trend. The decreasing trend rate ranged from −0.05 °C/year to 0.00 °C/year. The increasing trend of mean minimum temperature was significant at two stations (Gilgit and Bunji). The rate of increasing trend was between 0.01 °C/year and 0.06 °C/year. Overall, the study found a slight increase in mean maximum temperatures (TXmean) and mean minimum temperatures (TNmean) across the Himalayan region of Pakistan.

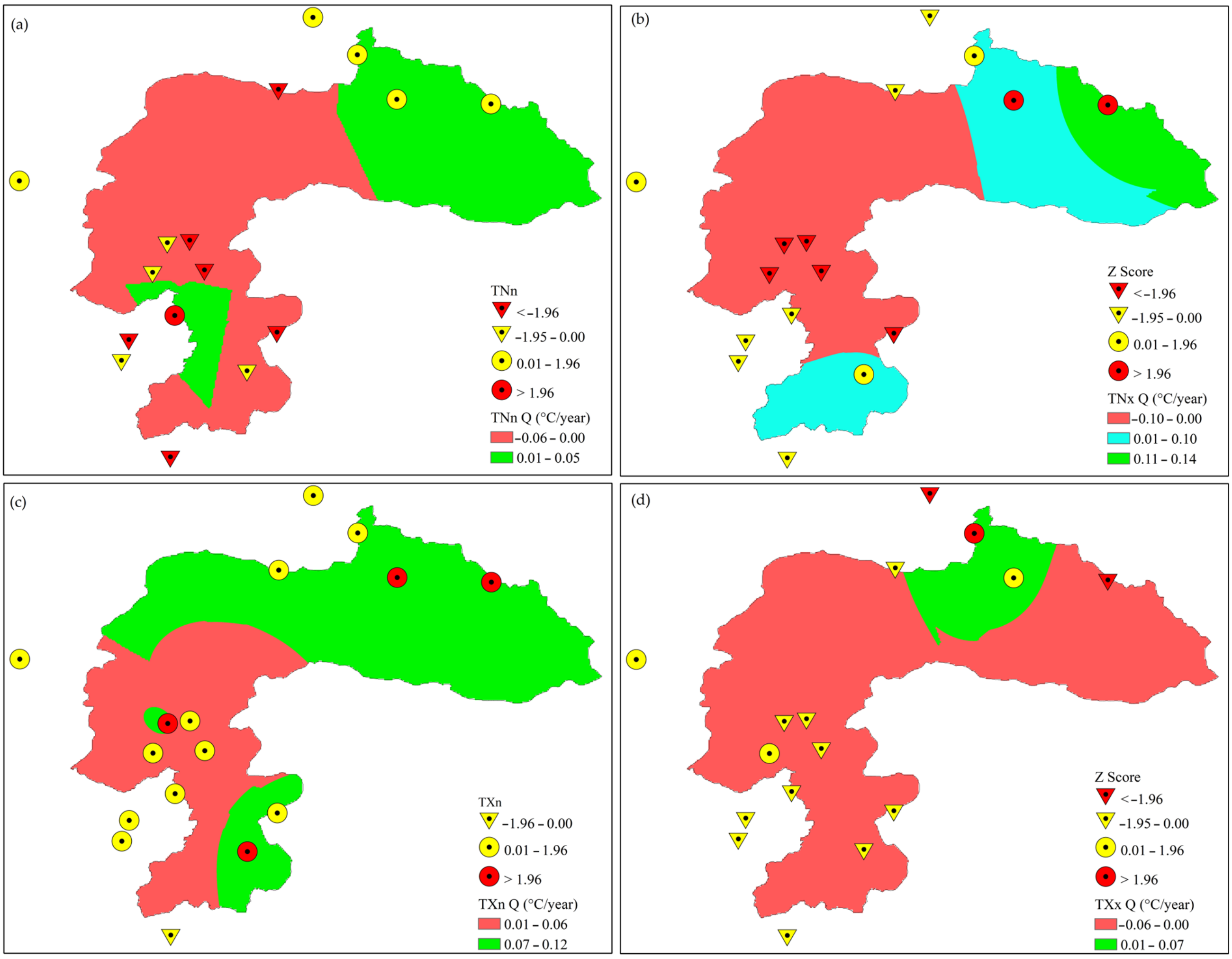

Figure 12. Spatial distribution maps of the Z and Q values for (**a**) TNn, (**b**) TNx, (**c**) TXn, and (**d**) TXx.

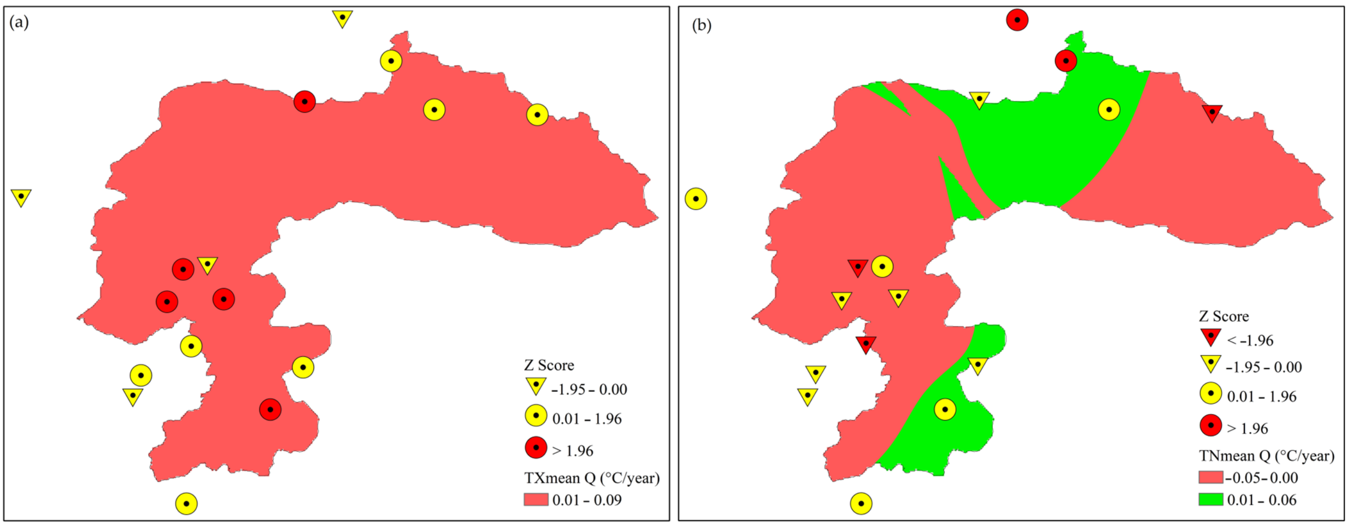

Figure 13. Spatial variation maps of Z and Q values for (**a**) TXmean and (**b**) TNmean.

4. Discussion

In order to obtain a clear understanding of the effects of climate change on various regions, it is crucial to examine the frequency and changing patterns of extreme weather events. This study thoroughly assessed the changes in extreme precipitation and temperature indices in the Himalayan Mountains of Pakistan from 1991 to 2020. The RClimDex 1.0 model was used to examine nine precipitation and fourteen temperature indices, offering a comprehensive evaluation of the trends and variations in climatic patterns. Furthermore, the utilization of the modified version of the Mann–Kendall test and TS slope estimator to examine trends and their slopes provides a more comprehensive and reliable analysis of the indices.

The study's findings suggest that there has been a decrease in extreme precipitation events in the Himalayan Mountains of Pakistan over the past 30 years. This is in line with trends of extreme precipitation events in different mountainous regions that are showing an increase in the frequency of drought events and a decrease in annual and seasonal precipitation [33,51,52]. Extreme precipitation events are becoming more intense, as evidenced by the increasing trend in the intensity-based indices [10,53,54]. The observed pattern can be linked to the persistent impacts of climate change, including increasing temperatures and changing air circulation patterns [55,56]. The interplay of various factors is causing shifts in precipitation patterns and intensities, resulting in the drying of once-wet regions and the further aridification of already-dry areas [57].

It is worth noting that there is an increasing trend in CDDs and a decreasing trend in CWDs. This indicates that the duration of dry extreme events is increasing, while the duration of wet extremes is declining. The results of this study have significant implications for the management of water resources and crop production in the region. Prolonged periods of dry conditions and fewer wet days can have negative effects on crop yields and exacerbate water stress. The diversity of trends of extreme precipitation indices in the Himalayan Mountains emphasizes the variation in the region's climate and the necessity of implementing regional climate adaptation strategies. The indices showed a more pronounced decline in some of the stations in the northern section of the research region, while other stations exhibited trends that were not significant or even a modest increase. These distinct characteristics underscore the significance of creating measures tailored to specific regions for the purpose of mitigation and adaptation. This finding aligns with the research conducted by previous studies [58].

Prior studies conducted in many different countries have documented an increase in the occurrence and intensity of hot days [5,57,59,60]. In this study, through the analysis of temperature indices, it has been concluded that the Himalayan Mountains in Pakistan have witnessed a rise in the number of hot days in the past three decades. This finding aligns with the results of a study conducted by Saleem et al. [60]. Consistent with the findings of Hussain et al. [22], this analysis also indicates that the daily maximum temperature has been steadily increasing over the past 30 years. Syed et al. [61] examined the patterns of extreme temperatures in Pakistan and found evidence of a rise in both the frequency and intensity of heat waves. We noticed a rise in the number of extremely hot days at several locations, which is consistent with their findings.

Temperature indices in the Himalayan Mountains have exhibited an upward trend over the last thirty years. The indices encompass maximum temperature (TMax), minimum temperature (TMin), warm days (TX90p), warm spell duration index (WSDI), diurnal temperature range (DTR), and coldest days (TXn). However, other temperature indices such as cold spell duration (CSDI), cold nights (TN10p), warm nights (TN90p), coldest nights (TNn), warmest nights (TNx), hottest days (TXx), cold days (TX10p), and tropical nights (TR20p) decreased during the same study period. The explanation for this phenomenon lies in the unique dynamics of mountain climates and the intricate interactions between atmospheric and geographical factors. Mountainous areas have unique terrain and elevations. The difference in warming tendencies between daytime and nighttime can be attributed to the impact of elevation on temperature patterns. Global warming can result in higher average daily maximum temperatures. However, the warming effect at higher elevations during nighttime may contribute to a rise in the number of hottest days experienced annually.

It is important to acknowledge that certain limitations in our study need to be considered when assessing the results. Firstly, due to the specific focus of this research that addresses the western part of the Himalayan Mountain in Pakistan, it is important to note that the findings may not be directly applicable to other parts of the mountain. To fully comprehend the patterns in other parts of the mountain, researchers in the future must examine how the frequency of extreme weather occurrences has changed across the mountain. Furthermore, our research spans a period of 30 years, from 1991 to 2020. While the current timeframe offers valuable insights into temporal trends, it is crucial to acknowledge that longer-term datasets can offer a more comprehensive understanding of climatic shifts. Increasing the study duration would allow for a more thorough examination of changes and enhance the precision of the identified patterns.

The results of this study could be expanded upon in several ways in future investigations. It is crucial to perform an initial analysis of the mechanisms behind the observed patterns in extreme precipitation and temperature events, as documented in this study. Studying the factors that influence these changes, such as air circulation patterns, land use changes, or the effects of aerosols, could offer a deeper comprehension of the shifts in temperature and precipitation extremes in the area. Additional research is required to examine the impact of shifting patterns in extreme weather events on different sectors, including water supply, agriculture, infrastructure, ecosystems, and public health. To promote resilience in light of changing climate patterns, it is critical to assess the sensitivity and adaptive ability of populations in the Himalayan mountains and to design effective adaptation methods.

5. Conclusions

The study examined the patterns of extreme temperature and precipitation indicators in the Himalayan Mountains from 1991 to 2020. This study documented significant changes in extreme precipitation and temperature events within the Himalayan Mountains of Pakistan, an area increasingly vulnerable to climate-induced disasters. Based on the data and analysis, the following conclusions were drawn:

- A consistent decline in total annual precipitation was noted, with an average decrease of −65.6 mm/decade, representing a drying pattern over the past thirty years (1991–2020).
- Annual average minimum and maximum temperatures exhibited rising trends, rising at rates of 0.20 °C/decade and 0.70 °C/decade, respectively, indicating a warming climate.
- Consecutive wet days (CWDs) and maximum 5-day precipitation (RX5day) demonstrated notable declines, with rates of −4.00 days/decade and −11.80 mm/decade, respectively, indicating a reduction in both the frequency and duration of wet periods.
- The quantity of precipitation on very wet days (R95p) and extremely wet days (R99p) has declined by −19.20 and −13.60 mm/decade, respectively, indicating a decrease in heavy precipitation occurrences.
- The duration of warm spells (WSDI) and the frequency of warm days (TX90p) have increased by 1.5 and 1.4 days/decade, respectively, indicating an increase in the occurrence and length of heatwave events.
- Cold days (TX10p) and cold nights (TN10p) have decreased significantly by 2.90 and 3.40 days/decade, respectively, indicating a trend toward warmer conditions.
- The diurnal temperature range (DTR) and the average temperature of the hottest nights (TXn) have increased by 0.30 °C and 0.10 °C per decade, respectively, indicating greater extremes in temperature variations.

The findings indicate a trend towards a drier and warmer climate in the Himalayan region, which may have significant consequences for water resources, agriculture, and disaster management. Based on the results of this study, decision-makers and other stakeholders in Pakistan's Himalayan region must prioritize building resilience and adaptive capacity to climate change. Localized adaptation measures are crucial for improving climate resilience and addressing the increasing threats from environmental changes.

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References

1. Akhtar, M.; Ahmad, N.; Booij, M.J. The Impact of Climate Change on the Water Resources of Hindukush-Karakorum-Himalaya Region under Different Glacier Coverage Scenarios. *J. Hydrol.* **2008**, *355*, 148–163. [CrossRef]
2. Pritchard, H.D. Asia's Glaciers Are a Regionally Important Buffer against Drought. *Nature* **2017**, *545*, 169–174. [CrossRef] [PubMed]
3. Rasul, G. Food, Water, and Energy Security in South Asia: A Nexus Perspective from the Hindu Kush Himalayan Region. *Environ. Sci. Policy* **2014**, *39*, 35–48. [CrossRef]
4. IPCC. Section 4: Near-Term Responses in a Changing Climate. In *AR6 Synthesis Report Climate Change*; IPCC: Geneva, Switzerland, 2023; pp. 42–66. [CrossRef]
5. Hussain, A.; Cao, J.; Hussain, I.; Begum, S.; Akhtar, M.; Wu, X.; Guan, Y.; Zhou, J. Observed Trends and Variability of Temperature and Precipitation and Their Global Teleconnections in the Upper Indus Basin, Hindukush-Karakoram-Himalaya. *Atmosphere* **2021**, *12*, 973. [CrossRef]
6. Karim, R.; Tan, G.; Ayugi, B.; Shahzaman, M.; Babaousmail, H.; Ngoma, H.; Ongoma, V. Projected Changes in Surface Air Temperature over Pakistan under Bias-Constrained CMIP6 Models. *Arab. J. Geosci.* **2023**, *16*, 205. [CrossRef]
7. Farhan, M.; Moazzam, U.; Rahman, G.; Munawar, S.; Tariq, A.; Safdar, Q.; Lee, B. Trends of Rainfall Variability and Drought Monitoring Using Standardized Precipitation Index in a Scarcely Gauged Basin of Northern Pakistan. *Water* **2022**, *14*, 1132. [CrossRef]
8. ul Hasson, S. Seasonality of Precipitation over Himalayan Watersheds in CORDEX South Asia and Their Driving CMIP5 Experiments. *Atmosphere* **2016**, *7*, 123. [CrossRef]
9. Abbas, S.; Yaseen, M.; Latif, Y.; Waseem, M.; Muhammad, S.; Leta, M.K.; Sher, S.; Imran, M.A.; Adnan, M.; Khan, T.H. Spatiotemporal Analysis of Climatic Extremes over the Upper Indus Basin, Pakistan. *Water* **2022**, *14*, 1718. [CrossRef]
10. Ezaz, G.T.; Zhang, K.; Li, X.; Shalehy, M.H.; Hossain, M.A.; Liu, L. Spatiotemporal Changes of Precipitation Extremes in Bangladesh during 1987–2017 and Their Connections with Climate Changes, Climate Oscillations, and Monsoon Dynamics. *Glob. Planet. Change* **2022**, *208*, 103712. [CrossRef]
11. Song, S.; Bai, J. Increasing Winter Precipitation over Arid Central Asia under Global Warming. *Atmosphere* **2016**, *7*, 139. [CrossRef]
12. Zaman, M.; Ahmad, I.; Usman, M.; Saifullah, M.; Anjum, M.N.; Khan, M.I.; Qamar, M.U. Event-Based Time Distribution Patterns, Return Levels, and Their Trends of Extreme Precipitation across Indus Basin. *Water* **2020**, *12*, 3373. [CrossRef]
13. Waseem, M.; Ajmal, M.; Ahmad, I.; Khan, N.M.; Azam, M.; Sarwar, M.K. Projected Drought Pattern under Climate Change Scenario Using Multivariate Analysis. *Arab. J. Geosci.* **2021**, *14*, 544. [CrossRef]
14. Spies, M. Mixed Manifestations of Climate Change in High Mountains: Insights from a Farming Community in Northern Pakistan. *Clim. Dev.* **2020**, *12*, 911–922. [CrossRef]
15. Mahmood, R.; Babel, M.S.; Jia, S. Assessment of Temporal and Spatial Changes of Future Climate in the Jhelum River Basin, Pakistan and India. *Weather Clim. Extrem.* **2015**, *10*, 40–55. [CrossRef]

16. Tahir, A.A.; Adamowski, J.F.; Chevallier, P.; Haq, A.U.; Terzago, S. Comparative Assessment of Spatiotemporal Snow Cover Changes and Hydrological Behavior of the Gilgit, Astore and Hunza River Basins (Hindukush–Karakoram–Himalaya Region, Pakistan). *Meteorol. Atmos. Phys.* **2016**, *128*, 793–811. [CrossRef]
17. Abbas, A.; Ullah, S.; Ullah, W.; Waseem, M.; Dou, X.; Zhao, C.; Karim, A.; Zhu, J.; Hagan, D.F.T.; Bhatti, A.S.; et al. Evaluation and Projection of Precipitation in Pakistan Using the Coupled Model Intercomparison Project Phase 6 Model Simulations. *Int. J. Climatol.* **2022**, *42*, 6665–6684. [CrossRef]
18. Łupikasza, E.B. Seasonal Patterns and Consistency of Extreme Precipitation Trends in Europe, December 1950 to February 2008. *Clim. Res.* **2017**, *72*, 217–237. [CrossRef]
19. Chen, F.; Chen, Y.; Bakhtiyorov, Z.; Zhang, H.; Man, W.; Chen, F. Central Asian River Streamflows Have Not Continued to Increase during the Recent Warming Hiatus. *Atmos. Res.* **2020**, *246*, 105124. [CrossRef]
20. Abbas, A.; Bhatti, A.S.; Ullah, S.; Ullah, W.; Waseem, M.; Zhao, C.; Dou, X.; Ali, G. Projection of Precipitation Extremes over South Asia from CMIP6 GCMs. *J. Arid Land* **2023**, *15*, 274–296. [CrossRef]
21. Al-Sakkaf, A.S.; Zhang, J.; Yao, F.; Hamed, M.M.; Simbi, C.H.; Ahmed, A.; Shahid, S. Assessing Exposure to Climate Extremes over the Arabian Peninsula Using ERA5 Reanalysis Data: Spatial Distribution and Temporal Trends. *Atmos. Res.* **2024**, *300*, 107224. [CrossRef]
22. Hu, W.; Chen, L.; Shen, J.; Yao, J.; He, Q.; Chen, J. Changes in Extreme Precipitation on the Tibetan Plateau and Its Surroundings: Trends, Patterns, and Relationship with Ocean Oscillation Factors. *Water* **2022**, *14*, 2509. [CrossRef]
23. Jiang, Z.; Li, W.; Xu, J.; Li, L. Extreme Precipitation Indices over China in CMIP5 Models. Part I: Model Evaluation. *J. Clim.* **2015**, *28*, 8603–8619. [CrossRef]
24. Azmat, M.; Liaqat, U.W.; Qamar, M.U.; Awan, U.K. Impacts of Changing Climate and Snow Cover on the Flow Regime of Jhelum River, Western Himalayas. *Reg. Environ. Change* **2017**, *17*, 813–825. [CrossRef]
25. Munawar, S.; Tahir, M.N.; Baig, M.H.A. Twenty-First Century Hydrologic and Climatic Changes over the Scarcely Gauged Jhelum River Basin of Himalayan Region Using SDSM and RCPs. *Environ. Sci. Pollut. Res.* **2022**, *29*, 11196–11208. [CrossRef]
26. Hamed, M.M.; Nashwan, M.S.; Shahid, S. Performance Evaluation of Reanalysis Precipitation Products in Egypt Using Fuzzy Entropy Time Series Similarity Analysis. *Int. J. Climatol.* **2021**, *41*, 5431–5446. [CrossRef]
27. Odnoletkova, N.; Patzek, T.W. Data-Driven Analysis of Climate Change in Saudi Arabia: Trends in Temperature Extremes and Human Comfort Indicators. *J. Appl. Meteorol. Climatol.* **2021**, *60*, 1055–1070. [CrossRef]
28. Saddique, N.; Khaliq, A.; Bernhofer, C. Trends in Temperature and Precipitation Extremes in Historical (1961–1990) and Projected (2061–2090) Periods in a Data Scarce Mountain Basin, Northern Pakistan. *Stoch. Environ. Res. Risk Assess.* **2020**, *34*, 1441–1455. [CrossRef]
29. Kothawale, D.R.; Revadekar, J.V.; Kumar, K.R. Recent Trends in Pre-Monsoon Daily Temperature Extremes over India. *J. Earth Syst. Sci.* **2010**, *119*, 51–65. [CrossRef]
30. Spinoni, J.; Naumann, G.; Carrao, H.; Barbosa, P.; Vogt, J. World Drought Frequency, Duration, and Severity for 1951–2010. *Int. J. Climatol.* **2014**, *34*, 2792–2804. [CrossRef]
31. Vogel, E.; Donat, M.G.; Alexander, L.V.; Meinshausen, M.; Ray, D.K.; Karoly, D.; Meinshausen, N.; Frieler, K. The Effects of Climate Extremes on Global Agricultural Yields. *Environ. Res. Lett.* **2019**, *14*, 054010. [CrossRef]
32. Feng, X.; Wang, Z.; Wu, X.; Yin, J.; Qian, S.; Zhan, J. Changes in Extreme Precipitation across 30 Global River Basins. *Water* **2020**, *12*, 1527. [CrossRef]
33. Ghanim, A.A.J.; Anjum, M.N.; Rasool, G.; Saifullah; Irfan, M.; Rahman, S.; Mursal, S.N.F.; Niazi, U.M. Assessing Spatiotemporal Trends of Total and Extreme Precipitation in a Subtropical Highland Region: A Climate Perspective. *PLoS ONE* **2023**, *18*, e0289570. [CrossRef] [PubMed]
34. Chapagain, D.; Dhaubanjar, S.; Bharati, L. Unpacking Future Climate Extremes and Their Sectoral Implications in Western Nepal. *Clim. Change* **2021**, *168*, 8. [CrossRef]
35. Khadka, N.; Zhang, G.; Thakuri, S. Glacial Lakes in the Nepal Himalaya: Inventory and Decadal Dynamics (1977–2017). *Remote Sens.* **2018**, *10*, 1913. [CrossRef]
36. Wood, L.R.; Neumann, K.; Nicholson, K.N.; Bird, B.W.; Dowling, C.B.; Sharma, S. Melting Himalayan Glaciers Threaten Domestic Water Resources in the Mount Everest Region, Nepal. *Front. Earth Sci.* **2020**, *8*, 128. [CrossRef]
37. Chintalapudi, S.; Sharif, H.O.; Xie, H. Sensitivity of Distributed Hydrologic Simulations to Ground and Satellite Based Rainfall Products. *Water* **2014**, *6*, 1221–1245. [CrossRef]
38. Anjum, M.N.; Ding, Y.; Shangguan, D.; Ahmad, I.; Ijaz, M.W.; Farid, H.U.; Yagoub, Y.E.; Zaman, M.; Adnan, M. Performance Evaluation of Latest Integrated Multi-Satellite Retrievals for Global Precipitation Measurement (IMERG) over the Northern Highlands of Pakistan. *Atmos. Res.* **2018**, *205*, 134–146. [CrossRef]
39. Hamza, A.; Anjum, M.N.; Cheema, M.J.M.; Chen, X.; Afzal, A.; Azam, M.; Shafi, M.K.; Gulakhmadov, A. Assessment of IMERG-V06, TRMM-3B42V7, SM2RAIN-ASCAT, and PERSIANN-CDR Precipitation Products over the Hindu Kush Mountains of Pakistan, South Asia. *Remote Sens.* **2020**, *12*, 3871. [CrossRef]
40. Nadeem, M.U.; Ghanim, A.A.J.; Anjum, M.N.; Shangguan, D.; Rasool, G.; Irfan, M.; Niazi, U.M.; Hassan, S. Multiscale Ground Validation of Satellite and Reanalysis Precipitation Products over Diverse Climatic and Topographic Conditions. *Remote Sens.* **2022**, *14*, 4680. [CrossRef]

41. Chu, P.S.; Chen, Y.R.; Schroeder, T.A. Changes in Precipitation Extremes in the Hawaiian Islands in a Warming Climate. *J. Clim.* **2010**, *23*, 4881–4900. [CrossRef]
42. Junzhi, L.; A-Xing, Z.; Zheng, D. Evaluation of TRMM 3B42 Precipitation Product Using Rain Gauge Data in Meichuan Watershed, Poyang Lake Basin, China. *J. Resour. Ecol.* **2012**, *3*, 359–366. [CrossRef]
43. Kang, B.-S.; Yang, S.-K.; Kang, M.-S. A Comparative Analysis of the Accuracy of Areal Precipitation According to the Rainfall Analysis Method of Mountainous Streams. *J. Environ. Sci. Int.* **2019**, *28*, 841–849. [CrossRef]
44. Ghanim, A.A.J.; Anjum, M.N.; Rasool, G.; Saifullah; Irfan, M.; Alyami, M.; Rahman, S.; Niazi, U.M. Analyzing Extreme Temperature Patterns in Subtropical Highlands Climates: Implications for Disaster Risk Reduction Strategies. *Sustainability* **2023**, *15*, 12753. [CrossRef]
45. Hamed, K.H.; Rao, A.R. A Modified Mann-Kendall Trend Test for Autocorrelated Data. *J. Hydrol.* **1998**, *204*, 182–196. [CrossRef]
46. Tan, M.; Duan, Z. Assessment of GPM and TRMM Precipitation Products over Singapore. *Remote Sens.* **2017**, *9*, 720. [CrossRef]
47. Li, J.; Heap, A.D. A Review of Comparative Studies of Spatial Interpolation Methods in Environmental Sciences: Performance and Impact Factors. *Ecol. Inform.* **2011**, *6*, 228–241. [CrossRef]
48. Ghajarnia, N.; Liaghat, A.; Daneshkar Arasteh, P. Comparison and Evaluation of High Resolution Precipitation Estimation Products in Urmia Basin-Iran. *Atmos. Res.* **2015**, *158–159*, 50–65. [CrossRef]
49. Mahmood, R.; Jia, S. Assessment of Impacts of Climate Change on the Water Resources of the Transboundary Jhelum River Basin of Pakistan and India. *Water* **2016**, *8*, 246. [CrossRef]
50. Yaseen, M.; Ahmad, I.; Guo, J.; Azam, M.I.; Latif, Y. Spatiotemporal Variability in the Hydrometeorological Time-Series over Upper Indus River Basin of Pakistan. *Adv. Meteorol.* **2020**, *2020*, 5852760. [CrossRef]
51. Waseem, M.; Khurshid, T.; Abbas, A.; Ahmad, I.; Javed, Z. Impact of Meteorological Drought on Agriculture Production at Different Scales in Punjab, Pakistan. *J. Water Clim. Change* **2022**, *13*, 113–124. [CrossRef]
52. Waseem, M.; Jaffry, A.H.; Azam, M.; Ahmad, I.; Abbas, A.; Lee, J.E. Spatiotemporal Analysis of Drought and Agriculture Standardized Residual Yield Series Nexuses across Punjab, Pakistan. *Water* **2022**, *14*, 496. [CrossRef]
53. Shiru, M.S.; Shahid, S.; Chung, E.S.; Alias, N. Changing Characteristics of Meteorological Droughts in Nigeria during 1901–2010. *Atmos. Res.* **2019**, *223*, 60–73. [CrossRef]
54. Wu, S.; Hu, Z.; Wang, Z.; Cao, S.; Yang, Y.; Qu, X.; Zhao, W. Spatiotemporal Variations in Extreme Precipitation on the Middle and Lower Reaches of the Yangtze River Basin (1970–2018). *Quat. Int.* **2021**, *592*, 80–96. [CrossRef]
55. Aslam, A.Q.; Ahmad, S.R.; Ahmad, I.; Hussain, Y.; Hussain, M.S. Vulnerability and Impact Assessment of Extreme Climatic Event: A Case Study of Southern Punjab, Pakistan. *Sci. Total Environ.* **2017**, *580*, 468–481. [CrossRef] [PubMed]
56. Saifullah, M.; Adnan, M.; Zaman, M.; Wałęga, A.; Liu, S.; Khan, M.I.; Gagnon, A.S.; Muhammad, S. Hydrological Response of the Kunhar River Basin in Pakistan to Climate Change and Anthropogenic Impacts on Runoff Characteristics. *Water* **2021**, *13*, 3163. [CrossRef]
57. Xu, D.; Liu, D.; Yan, Z.; Ren, S.; Xu, Q. Spatiotemporal Variation Characteristics of Precipitation in the Huaihe River Basin, China, as a Result of Climate Change. *Water* **2023**, *15*, 181. [CrossRef]
58. Bhatti, A.S.; Wang, G.; Ullah, W.; Ullah, S.; Hagan, D.F.T.; Nooni, I.K.; Lou, D.; Ullah, I. Trend in Extreme Precipitation Indices Based on Long Term in Situ Precipitation Records over Pakistan. *Water* **2020**, *12*, 797. [CrossRef]
59. Hidalgo García, D.; Arco Díaz, J.; Martín Martín, A.; Gómez Cobos, E. Spatiotemporal Analysis of Urban Thermal Effects Caused by Heat Waves through Remote Sensing. *Sustainability* **2022**, *14*, 12262. [CrossRef]
60. Saleem, F.; Zeng, X.; Hina, S.; Omer, A. Regional Changes in Extreme Temperature Records over Pakistan and Their Relation to Pacific Variability. *Atmos. Res.* **2021**, *250*, 105407. [CrossRef]
61. Syed, A.; Liu, X.; Moniruzzaman, M.; Rousta, I.; Syed, W.; Zhang, J.; Olafsson, H. Assessment of Climate Variability among Seasonal Trends Using In Situ Measurements: A Case Study of Punjab, Pakistan. *Atmosphere* **2021**, *12*, 939. [CrossRef]