RESEARCH ARTICLE
AGROBIOLOGICAL RECORDS
ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

TREND ANALYSIS OF EXTREME WEATHER INDICES IN DIFFERENT DISTRICTS OF PUNJAB, PAKISTAN

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ABSTRACT

The objective of this research is to analyze trends in extreme daily temperature and precipitation indices at six meteorological stations in Punjab, including Faisalabad, Khanpur, Lahore, Sialkot, Mianwali, and Murree. Climate indices were calculated using rainfall and temperature data from 1991 to 2022, using the RClimpact2 R software package. The Mann-Kendall test was applied to assess trends. The results show an upward trend in very warm days (TX95t) and warm nights (TN90p) across all stations. However, other indicators such as summer days (SU25), warm days (TX90), the warm spell duration indicator (WSDI), maximum and minimum temperatures (TXx, TNn), diurnal temperature range (DTR), cool days (TX10p), cool nights (TN10p) and spell duration indicator (SPI) displayed variability. Similarly, precipitation indices, including Simple rainfall intensity index (SDII), Max 1-day rainfall amount (RX1day), Max 5-day rainfall amount (RX5day), Number of heavy rainfall days (R10), Number of very heavy rainfall days (R20), consecutive dry days (CDD), Consecutive wet days (CWD), Very wet days (R95p), Extremely wet days (R99p) and annual total wet-day rainfall (PRCPTOT) showed mixed trends across the stations. Most of these trends were not statistically significant at the 0.05 level, although an increase in maximum daytime temperature was observed at five of the six stations. The findings suggest that changes in temperature and precipitation patterns are minor and inconsistent, both temporally and spatially. There is a crucial need for more comprehensive annual data from a broader range of weather stations in Punjab to evaluate ongoing and significant climatic changes in the region.

Keywords: RClimpact2, Climate change, Climate indices, Climate trends and MK test

Article History (ABR-24-251) || Received: 17 Aug 2024 || Revised: 17 Oct 2024 || Accepted: 20 Oct 2024 || Published Online: 22 Oct 2024

1. INTRODUCTION

Punjab, located in central-eastern Pakistan, experiences a hot semi-arid climate with significant temperature variations between summer and winter. Temperatures range from −2 to 45°C, occasionally reaching as high as 50°C in the summer and dropping as low as −10°C in the winter. Climate variability significantly affects various socioeconomic activities, particularly agriculture. This study examines the frequency, causes, and risks associated with climate variability and extreme climate indices across Punjab (Aslam et al. 2017).

The 21st century is projected to see moderate warming, particularly in high-latitude regions during winter, along with a decrease in temperature variability (Ullah et al. 2022). Recently, Punjab has experienced significant temperature variability resulting in prolonged droughts and irregular monsoon seasons, often leading to severe flooding (Adnan and Ullah 2022). A warming trend of 0.22°C was observed in Faisalabad between 1945 and 2004 (Saqib and Gill 2019). Research covering the period from 1961 to 2014 indicates increasing maximum temperatures in spring (0.028°C per year) and decreasing summer temperatures (-0.013°C/year), along with rising minimum temperatures across other seasons (Khattak and Ali, 2015). Rising surface temperatures affect seed germination and increase evapotranspiration rates (Arshad et al. 2023), while irrigation alters the balance of temperature and humidity (Hossain et al. 2021). Temperature extremes is essential for managing the impacts of climate change (Lesk et al. 2022).

Punjab's climate has significant variability, with extreme temperatures affecting agriculture. Accurate forecasting is essential for mitigating these impacts and improving agricultural planning. The simple exponential smoothing method has proven effective for short-term temperature predictions in the region (Baykal et al. 2022). Projections suggest more frequent and severe heat events and fewer extreme cold in Punjab. Since 1991, hot days and nights have increased, while extremely cold days and nights have decreased. From 1991 to 2020, cold days have decreased, and days with maximum temperatures exceeding the 90th

Citation: Ameen I, Kashif M, Hameed HN and Nida H, 2024. Trend analysis of extreme weather indices in different districts of Punjab, Pakistan. Agrobiological Records 18: 29-40. https://doi.org/10.47278/journal.abr/2024.035

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
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percentile have shown a declining trend (Ravindra et al. 2024). Recent studies underscore evolving climate extremes in the region. They observed a significant trend in extreme temperature indices across South Asia (Peng et al. 2023). Dilawar et al (2021) reported impacts on agricultural productivity in Punjab due to increased climate variability. These findings highlight the need for adaptive agricultural strategies. Analysis of diurnal temperature range (DTR) and air temperatures from 1991 to 2020 revealed a marked increase in nighttime temperatures at some meteorological stations, while daytime temperatures have shown a modest rise. The observed trends indicate negative DTR trends over the past 30 years. To assess climatic variations, daily temperature and rainfall data were analyzed using the Mann-Kendall test, which showed a general trend of rising temperatures (Zhong et al., 2023). This research aims to evaluate extreme temperature frequencies and trends from 1991 to 2020, using nine temperature indices across nine meteorological stations, crucial for understanding climate impacts on agriculture.

The main objectives of this study are to model the variation and prediction of trends in the temperature and rainfall data of different districts in Punjab and to analyze the frequency and patterns of extreme indices in the climate variability of different districts in Punjab.

2. MATERIALS AND METHODS

Time series data for precipitation (P), maximum temperature (Tmax), and minimum temperature (Tmin) over a 30-year period (1991–2020) were collected from six meteorological stations in Punjab: Faisalabad, Lahore, Khanpur, Sialkot, Murree, and Mianwali. The data were obtained from the Pakistan Meteorological Department. A set of 22 core climate indices (12 for temperature and 10 for rainfall) are calculated by using RClimpact2 software Package.

Table 1 presents the annual average values for Tmax, Tmin and Tmean from 1991 to 2020 at six meteorological stations in Punjab, Pakistan. Mianwali station records the highest average Tmax at 51.0°C, indicating extreme heat, while Murree, due to its higher altitude, has the lowest Tmax at 34.5°C. Murree also experiences the lowest Tmin at -10.0°C, consistent with its cooler climate, whereas Khanpur records an extreme low of -8.0°C despite its generally hot conditions. In terms of Tmean, Lahore has the highest at 24.82°C, indicating relatively moderate temperatures throughout the year, while Murree, with a Tmean of 13.35°C, remains the coolest among the stations. These variations highlight the diverse climatic conditions across Punjab, shaped by geographical and environmental factors.

Table 1: Annual average values from 1991 to 2020, and the types of meteorological stations used in the study.

Meteorological Stations	Tmax(°C)	Tmin(°C)	Tmean(°C)
Faisalabad	48.2	-3.0	24.38
Lahore	47.1	1.1	24.82
Khanpur	50.8	-8.0	24.21
Sialkot	47.0	-2.0	23.12
Murree	34.5	-10.0	13.35
Mianwali	51.0	-3.5	21.21

Table 2 provides the geographical coordinates (latitude, longitude, and altitude) of six meteorological stations in Punjab, Pakistan, along with the percentage of missing data for Tmax, Tmin and P from these stations. The stations are located at different altitudes, with Murree being the highest at 2,291 meters and Khanpur the lowest at 290 meters. The percentage of missing data varies across the stations, with Mianwali having the highest data gaps, particularly in Tmax and Tmin, with nearly 10% missing. In contrast, Murree has relatively low missing data, with about 2.15% for both Tmax and Tmin. Other stations such as Faisalabad, Lahore and Sialkot, show missing data percentages between 1.84% and 2.92%, indicating generally good data availability. However, Khanpur shows slightly higher missing data, especially for Tmin (4.46%). These variations in missing data highlight potential challenges in data continuity, which could affect the reliability of long-term climate trend analyses for some stations, especially Mianwali. Only stations with less than 20% missing data were included in the analysis. Outliers for missing values in Tmax, Tmin and P were identified and set to -99.9. For rainfall, the daily values of monthly maxima were used as the upper limit for outlier detection. The quality of the data was assessed for both minimum and maximum temperature values. Additionally, Quality Control (QC) procedures were implemented to identify anomalies in daily minimum and maximum temperatures as well as rainfall. After inputting the station data, QC checks in RClimpact2 indicated no significant deviations in the daily temperature and rainfall data from the selected weather stations. The annual trends of the selected indices were determined using a linear least squares approach in RClimpact2. Trend significance was evaluated using Sen's slope estimator, with trends considered significant if the p-value was less than 0.05 at the 95% confidence level, in accordance with the

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hypothesis testing approach (Zhang et al. 2018).

Table 2: Geographical coordinates of used stations, as well as the percentage of missing data

Stations	Latitude	Longitude	Altitude	Missing data (%)		
				Tmax	Tmin	P
Faisalabad	31.4504	73.1350	186	1.86	1.84	2.92
Lahore	31.5204	74.3587	217	2.17	1.90	2.08
Sialkot	32.4945	74.5229	256	2.86	2.48	2.22
Khanpur	28.6332	70.6574	290	4.05	4.46	2.94
Murree	33.9070	73.3943	2,291	2.15	2.15	1.95
Mianwali	32.5839	71.5370	210	9.99	10.15	2.50

2.1. Mann–Kendall (MK) Test

The Mann–Kendall (MK) test was employed to assess non-stationary variations in rainfall extremes across various districts of Punjab. This well-known non-parametric technique is effective for detecting monotonic trends in climate data.

The Mann-Kendall test statistics computed as:

$$S=\sum_{k=1}^{n-1}\sum_{j=k+1}^{n}\operatorname{sgn}\left(Y_j-Y_k\right) \quad (1)$$

$$\operatorname{sgn}(y)=\begin{cases}1 & \text{if } y>0,\\ 0 & \text{if } y=0,\\ -1 & \text{if } y<0.\end{cases}$$

The mean of S is $E[S]=0$ and the variance $p\le 0.05$ is

$$\sigma^2=\frac{1}{18}\left\{n(n-1)(2n-1)-\sum_{j=1}^{p}p_j(p_j-1)(2p_j+5)\right\}, \quad (2)$$

where

p_j is the number of data points in the p^{th} tied group and p is the number of tied groups in the data set.

If the following Z -transformation is used, the statistic S is approximately normal distributed

$$Z=\begin{cases}\dfrac{R-1}{\sigma} & \text{if } R>0,\\ 0 & \text{if } R=0,\\ \dfrac{R+1}{\sigma} & \text{if } R<0.\end{cases}$$

The statistic R is strongly related to Kendall's τ as given by:

$$\tau=\frac{R}{D},$$

where

$$D=\left[\frac{1}{2}n(n-1)-\frac{1}{2}\sum_{j=1}^{p}p^j(p^j-1)\right]^{\frac{1}{2}}\left[\frac{1}{2}n(n-1)\right]^{\frac{1}{2}} \quad (3)$$

RClimpact2 was used to verify and control the quality of climate data from six stations. Missing data were identified and recorded for each station, and the percentage of missing data was calculated for the selected stations. It was found that the percentage of missing climate data was higher before 1991, with significant data gaps in certain areas of Punjab. Stations with the highest proportion of continuously available climate data were chosen, ensuring that the proportion of missing data over the 30-year period was less than 5%. These selected stations were then formatted in RClimpact2 for further quality assurance and control (Sharma et al. 2022).

Table 3 presents a set of climate extreme indices used to assess temperature extremes. These indices include measures such as SU25, which counts the number of days each year when the daily maximum temperature exceeds 25°C, and FD counts the annual days with minimum temperatures below 0°C. TXx and TNn represent the highest and lowest daily temperatures recorded in a month, respectively. DTR measures the average monthly difference between maximum and minimum temperatures. Indices like CSDI6 and WSDI track the duration of cold and warm spells by counting the days within periods of extreme temperatures. Percentile-based indices such as TX95t, TN10p, and TX90p indicate thresholds for very warm days, cool nights, and warm days. Together, these indices provide a comprehensive view of temperature extremes, highlighting variations in daily and seasonal temperature

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
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patterns (Zhang et al. 2011).

Table 3: List of the selected climate extreme indices for temperature

Sr. No	Index	Name	Definitions	Units
1	SU25	Summer days	Annual count when TX (daily maximum) > 25 °C	Days
2	TXx	Maximum temperature	Maximum daily value recorded in a month	°C
3	TNn	Minimum temperature	Minimum daily value recorded in a month	°C
4	DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C
5	FD	Frost days	Annual count when TN (daily minimum) < 0 °C	Days
6	CSDI6	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN < 10th percentile	Days
7	WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX > 90th percentile	Days
8	TX95t	Very warm day threshold	Value of 95th percentile of TX	°C
9	TN10p	Cool nights	Percentage of days when TN < 10th percentile	Days
10	TN90p	Warm nights	Percentage of days when TN > 90th percentile	Days
11	TX10p	Cool days	Percentage of days when TX < 10th percentile	Days
12	TX90p	Warm days	Percentage of days when TX > 90th percentile	Days

RX1day, which measures the maximum amount of rainfall recorded in a single day within a month, and Rx5day, which captures the maximum cumulative rainfall over a consecutive five-day period in a month. The SDII calculates the annual total rainfall divided by the number of wet days, defined as days with precipitation of 1.0mm or more. R10 and R20 indicate the annual count of days with heavy (10mm or more) and very heavy (20mm or more) rainfall, respectively (Table 4). CDD tracks the maximum number of consecutive days with less than 1mm of rainfall, while CWD measures the maximum number of consecutive days with 1mm or more of rainfall. Indices such as R95p and R99p reflect the annual total precipitation on days exceeding the 95th and 99th percentiles of rainfall, respectively. Finally, PRCPTOT represents the total annual precipitation on wet days (Table 4). These indices provide valuable insights into the intensity, duration and frequency of rainfall events, capturing various aspects of rainfall extremes (Chen et al. 2024).

Table 4: List of the selected climate extreme indices for rainfall

Sr. No	Index	Name	Definitions	Units
1.	RX1day	Max 1-day rainfall amount	Monthly maximum 1-day rainfall	°C
2.	Rx5day	Max 5-day rainfall amount	Monthly maximum consecutive 5-day rainfall	Mm
3.	SDII	Simple rainfall intensity index	Annual total rainfall divided by the number of wet days (defined as PRCP>=1.0mm) in the year	Mm/days
4.	R10	Number of heavy rainfall days	Annual count of days when PRCP>=10mm	Days
5.	R20	Number of very heavy rainfall days	Annual count of days when PRCP>=20mm	Days
6.	CDD	Consecutive dry days	Maximum number of consecutive days with RR<1mm	Days
7.	CWD	Consecutive wet days	Maximum number of consecutive days with RR>=1mm	Days
8.	R95p	Very wet days	Annual total PRCP when RR>95th percentile	Mm
9.	R99p	Extremely wet days	Annual total PRCP when RR>99th percentile	Mm
10.	PRCPT OT	Annual total wet-day rainfall	Annual total PRCP in wet days (RR>=1mm)	Mm

3. RESULTS AND DISCUSSION

3.1. Data Exploration

A district-wise analysis of observed climatic indices indicates significant trends of both increase and decrease over the established baseline timeframe (Sajjad and Ghaffar 2019; Das et al. 2024). The linear trends depicted in the selected indices' plots illustrate the varying directions of extreme climate indices. The climatological records for both maximum and minimum temperatures exhibit a substantial level of concurrence with the observed data from select districts in Punjab (Ali et al. 2022).

The climatological data for both maximum and minimum temperatures demonstrate a notable convergence with the observations recorded across multiple districts within Punjab, Pakistan. Regarding precipitation patterns, modeling centers effectively capture winter precipitation peaks with high accuracy; discrepancies arise in the timing of monsoon onset and withdrawal when compared to actual observations (Bombardi et al. 2020; Khan et al. 2021). Notably, the representation of winter precipitation across diverse districts of Punjab lacks precision in the modeling outputs, highlighting a need for refinement in accurately depicting these variations (Imran et al. 2020).

After completing the data quality verification, climate indices were calculated using the RClimpact2 program, based on the Adjusted Series. This program is developed by a team of experts to detect climate change and utilizes various indices to measure frequency, duration, intensity, and temperature extremes from daily time series (Table 5). The subsequent step involved analyzing trends in the signal series over the research period. Trend analysis was conducted using the non-parametric Mann-Kendall (MK) test, which calculates the Tau statistic. In this study, Tau

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values ranged between -1 and +1 (or -4 and +4 as per Senior's 1990 guidelines), with positive values indicating upward trends and negative values indicating downward trends (Hussain and Mahmud 2019; Malik and Kumar, 2020).

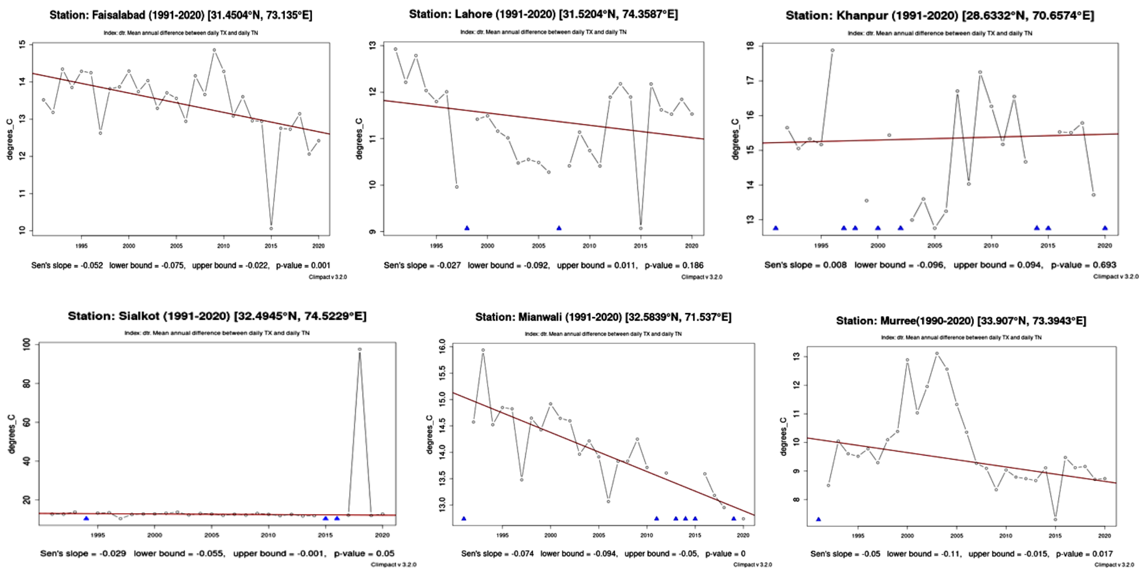
Table 5: Trends in terms of temperature and rainfall

Indices	Faisalabad		Lahore		Khanpur		Sialkot		Murree	
	Tau	P- value	Tau	P-value	Tau	P-value	Tau	P-value	Tau	P-value
SU25	-0.064	0.829	-0.245	0.405	0.42	0.274	0.126	0.708	-0.007	0.978
WSDI	-0.079	0.515	-0.389	0.137	0.293	0.07	0.088	0.681	0.016	0.919
Txx	-0.025	0.377	-0.015	0.574	-0.772	0.629	0.028	0.337	-0.046	0.263
Tx95t	0.004	0.22	0.004	0.307	0.003	0.397	0.001	0.696	0.01	0
FD	0.006	0.844	0	0	-0.113	0.047	0.206	0.126	-1.444	0.013
CSDI	-0.321	0.036	-0.122	0.515	-0.189	0.104	-0.092	0.675	-0.507	0.405
CSDI6	-0.321	0.036	-0.122	0.515	-0.189	0.104	-0.092	0.675	-0.507	0.405
TNn	-0.005	0.861	-0.014	0.631	0.115	0.006	-6.728	0.129	0.106	0.017
DTR	-0.054	0.004	-0.023	0.235	-0.045	0.036	0.545	0.15	-0.067	0.031
TN10p	-0.361	0	-0.021	0.87	-0.495	0.001	-0.271	0.028	-0.505	0.055
TN90p	0.259	0.005	0.026	0.856	0.563	0	0.208	0.086	0.233	0.091
RX1day	0.126	0.832	0.268	0.767	-0.272	0.786	1.022	0.355	-2.076	0.058
RX5day	0.126	0.901	0.555	0.794	-0.798	0.59	2.016	0.452	-4.363	0.007
SDII	-0.014	0.823	0.006	0.934	0.014	0.827	0.064	0.412	-0.95	0.001
R10	0.126	0.202	0.183	0.17	0.058	0.411	0.028	0.833	-0.386	0.052
R20	0.109	0.055	0.042	0.628	0.014	0.69	0.053	0.638	-0.275	0.104
CDD	-0.988	0.129	0.491	0.461	1.58	0.113	-0.013	0.979	-0.0036	0.903
CWD	0.037	0.117	-0.022	0.559	-0.029	0.339	0.008	0.824	-0.081	0.096
R95p	1.493	0.518	0.715	0.846	0.482	0.772	0.334	0.954	-14.411	0.001
R99p	-0.329	0.801	0.778	0.724	-0.277	0.826	0.931	0.792	-6.996	0.02
PRCPTOT	5.914	0.071	3.715	0.474	0.002	0.914	2.069	0.766	-18.322	0.01
TX10p	0.035	0.731	0.129	0.27	-0.2281	0.041	0.002	0.984	-0.028	0.751

3.2 Observed Indices of Punjab

There are the following climate indices that observed in selected districts of Punjab.

3.2.1. DTR (Diurnal temperature range): The following time series graphs in Fig. 1 show the mean difference between monthly maximum temperature and minimum temperature in selected stations of Punjab per year. Sialkot is showing a rising trend, which means the trend is positive, with 0.545% days every year from 1991 to 2020 (Sumair et al. 2023). While the other five stations, Faisalabad, Lahore, Khanpur, Murree, and Mianwali, represent a negative trend that shows a decreasing trend with -0.054, -0.023, -0.043, -0.067 and -0.101% mean difference monthly period over a year (Syed et al. 2021) The trend of all stations are 0 to 0.004 statistically significant. The estimated index shows the total average of the monthly maximum and minimum temperature days per year from 1991 to 2020 are Faisalabad 13.40, Khanpur has -27.28, Lahore has 3.90, Sialkot has 4.17, Murree has 6.14, and Mianwali has -5.06.



ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
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Fig. 1: DTR of six stations from 1991 to 2020.

3.2.2. WSDI Indices (Annual count of days with at least 6 consecutive days when maximum temperature > 90th percentile): Following time series graphs in Fig. 2 showing the warm spell duration index means the number of annual days with the minimum of 6 consecutive days on which maximum temperature in greater than 90th percentile in Punjab. Khanpur, Sialkot, and Murree show rising trend that means trend is positive with 0.293, 0.088, and 0.016% days over every year from 1991 to 2020. While other three stations, Faisalabad, Lahore, and Mianwali represent the negative trend that show the decreasing trend with -0.079, -0.389, and -0.177% warm period days over a year (Nawaz et al. 2019). The trend of all stations are 0.01 to 0.07 level of significance. The estimated index shows the total average of warm spell days that was higher than 90th percentile per year from 1991 to 2020 are Faisalabad have 4.24, Khanpur have -24.24, Lahore have 4.00, Sialkot have 0.40, Murree have 3.43, and Mianwali have -12.75 (Shirazi et al. 2019).

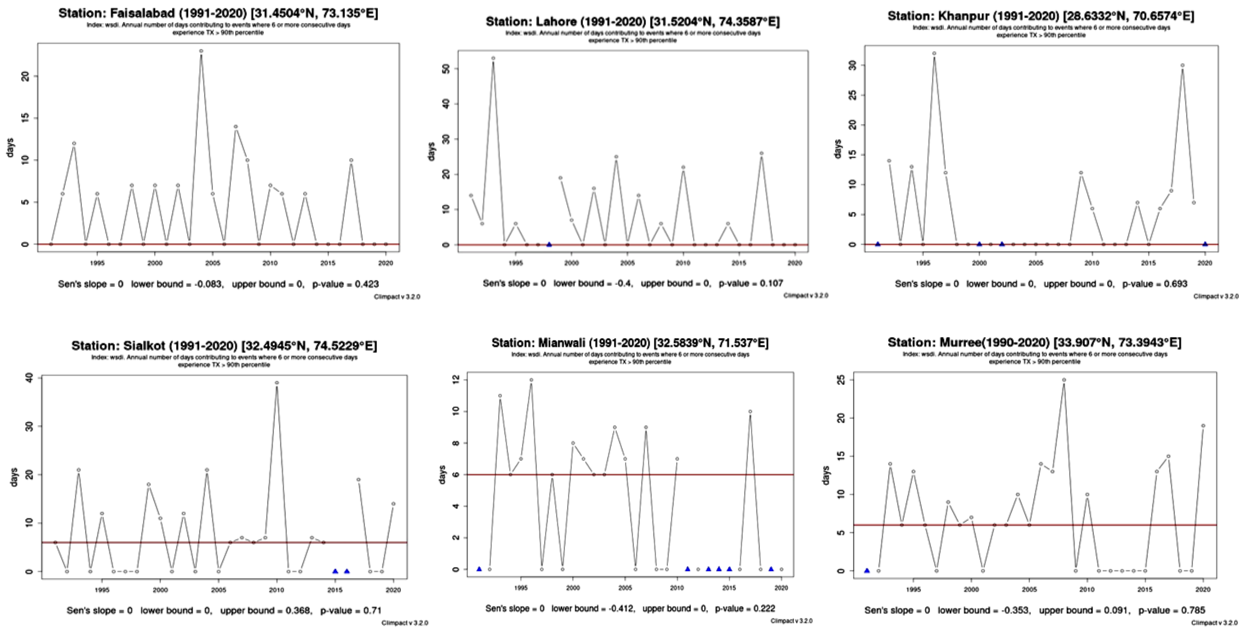

Fig. 2: WSDI of six stations from 1991 to 2020.

3.2.3: FD Indices (Annual count when daily minimum temperature < 0°C): Following time series graphs in Fig. 3 made for frost days index that indicates that days when minimum temperature lower than 0oC in selected stations of Punjab per year. Faisalabad, Sialkot and Mianwali showing rising trend that means trend is positive with 0.006, 0.206 and 0.509% days over every year from 1991 to 2020. While Lahore showing zero trend and other stations Khanpur, and Murree representing the negative trend that show the decreasing trend with -0.113, and -1.444% over a year. The trend of all stations are 0.04 to 0.09 statistically significant. Estimated index shows the total average when minimum temperature lower than 0°C of per year from 1991 to 2020 are Faisalabad have 0.56, Khanpur have -21.17, Lahore have 0, Sialkot have -8.75, Murree have 53.97, and Mianwali have -13.78.

3.2.4: SDII Indices (Annual total precipitation divided by the number of wet days defined as PRCP>=1.0mm in the year): Following time series graphs in Fig. 4 show the simple daily intensity index in which the annual total amount of precipitation divided by the number of wet days as precipitation should be greater than is equal to 1.0 mm in selected stations of Punjab. Lahore, Khanpur, and Sialkot show rising trends, which means the trend is positive, with 0.006, 0.014, and 0.064% days over every year from 1991 to 2020. While the other three stations, Faisalabad, Murree, and Mianwali, represent a negative trend that shows a decreasing trend with -0.014, -0.15, and -0.095% minimum warmest monthly period over a year (Malik et al. 2021). The trend of all stations are 0.01 to 0.4 statistically significant. Estimated index shows the total average of monthly minimum temperature days of per year from 1991 to 2020 are Faisalabad have 4.22, Khanpur have -4.99, Lahore have 10.38, Sialkot have 8.29, Murree have 11.67, and Mianwali have 2.30.

3.2.5: R10 Indices (Annual count of days when PRCP>=10mm): The following time series graphs in Fig. 5 show the number of heavy precipitation indexes when the amount of precipitation is greater than is equal to 10mm in selected stations of Punjab. Faisalabad, Lahore, Khanpur, and Sialkot show a rising trends, which means the trend is

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
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positive (Sarfaraz and Faisal 2023) with 0.126, 0.183, 0.058, and 0.028% days over every year from 1991 to 2020. The other two stations, Murree and Mianwali, represent a negative trend that shows a decreasing trend with -0.386 and -0.103% minimum warmest period monthly days over a year. The trend of all stations are 0.05 to 0.4 statistically significant. Estimated index shows the total average of heavy precipitation when amount of precipitation greater than is equal 10 mm of per year from 1991 to 2020 are Faisalabad have 4.61, Khanpur have -7.96, Lahore have 14.64, Sialkot have 18.61, Murree have 45.88, and Mianwali have 5.61.

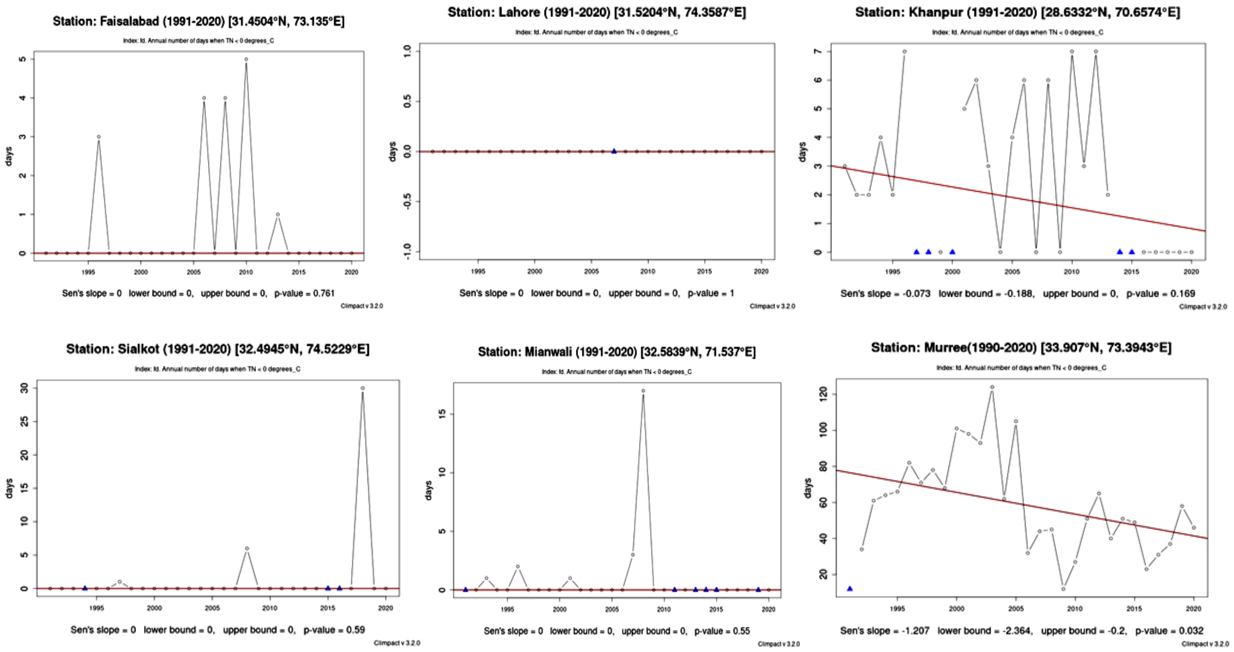

Fig. 3: FD of six stations from 1991 to 2020.

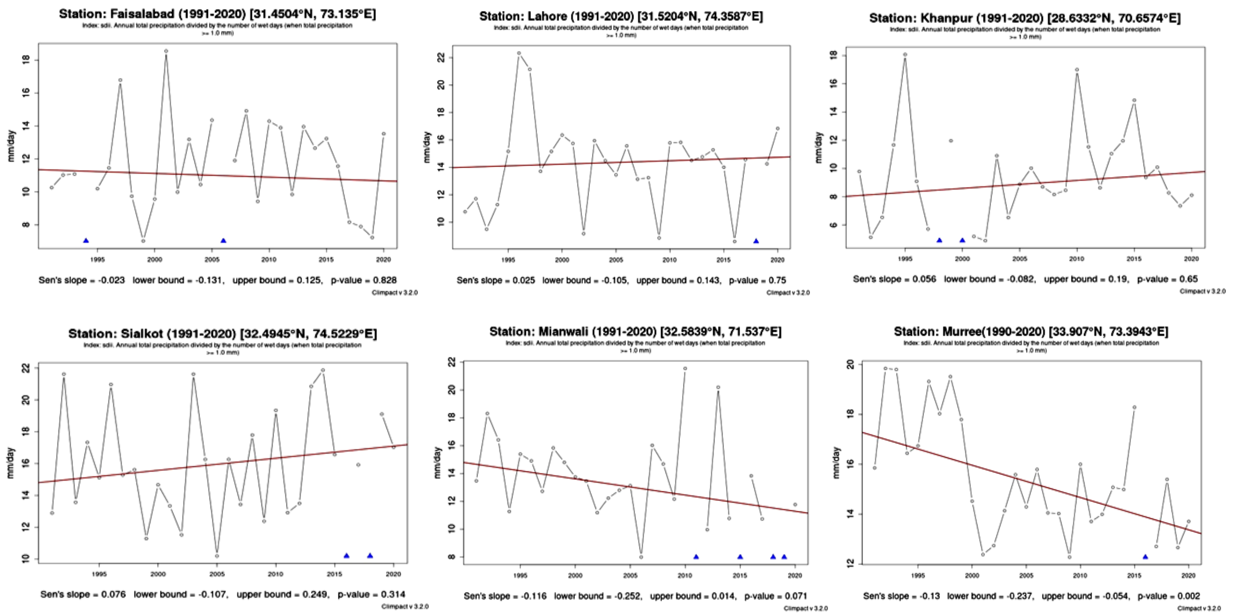

Fig. 4: SDII of six stations from 1991 to 2020.

3.2.6. R20 Indices (Annual count of days when PRCP>=20mm): Following time series graphs in Fig. 6 showing the number of very heavy rainfall index when the amount of rainfall was greater than is equal 20mm in selected stations of Punjab. Faisalabad, Lahore, Khanpur and Sialkot showed rising trend that means trend is positive with 0.109, 0.042, 0.014 and 0.053% days over every year from 1991 to 2020.While other two stations, Murree, and Mianwali representing the negative trend that show the decreasing trend with -0.275, and -0.107% minimum

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ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
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warmest period monthly days over a year. The trend of all stations are 0.05 to 0.6 statistically significant. Estimated index shows the total average of heavy precipitation when amount of precipitation greater than is equal 20 mm of per year from 1991 to 2020 are Faisalabad have -0.89, Khanpur have -11.09, Lahore has 6.81, Sialkot have 8.51, Murree have 24.37, and Mianwali have -1.29.

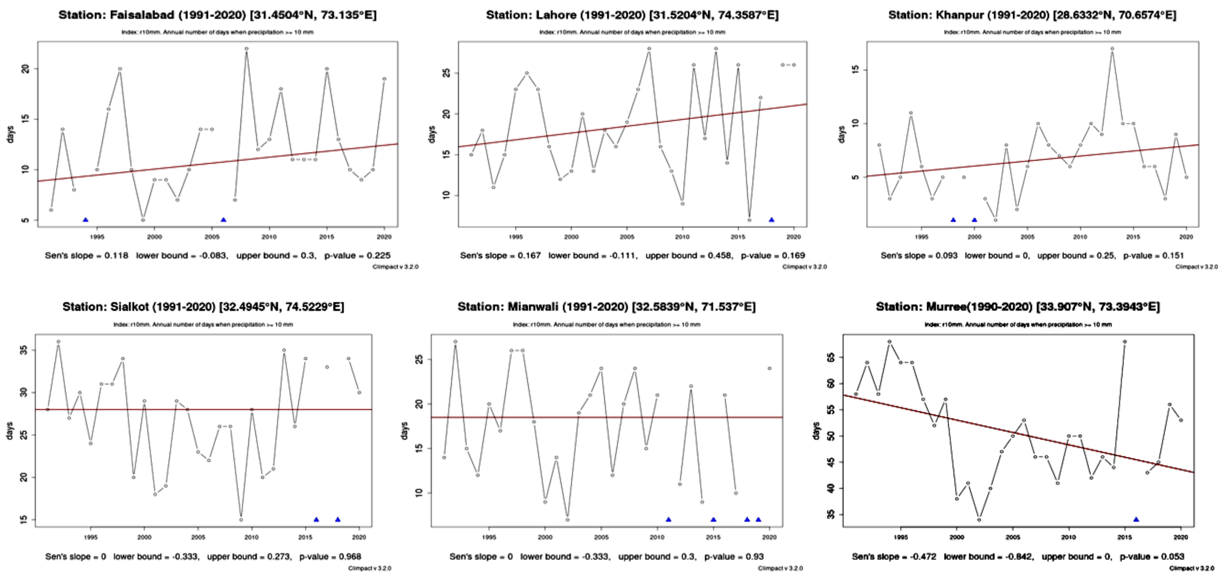


Fig. 5: R10 of six stations from 1991 to 2020.

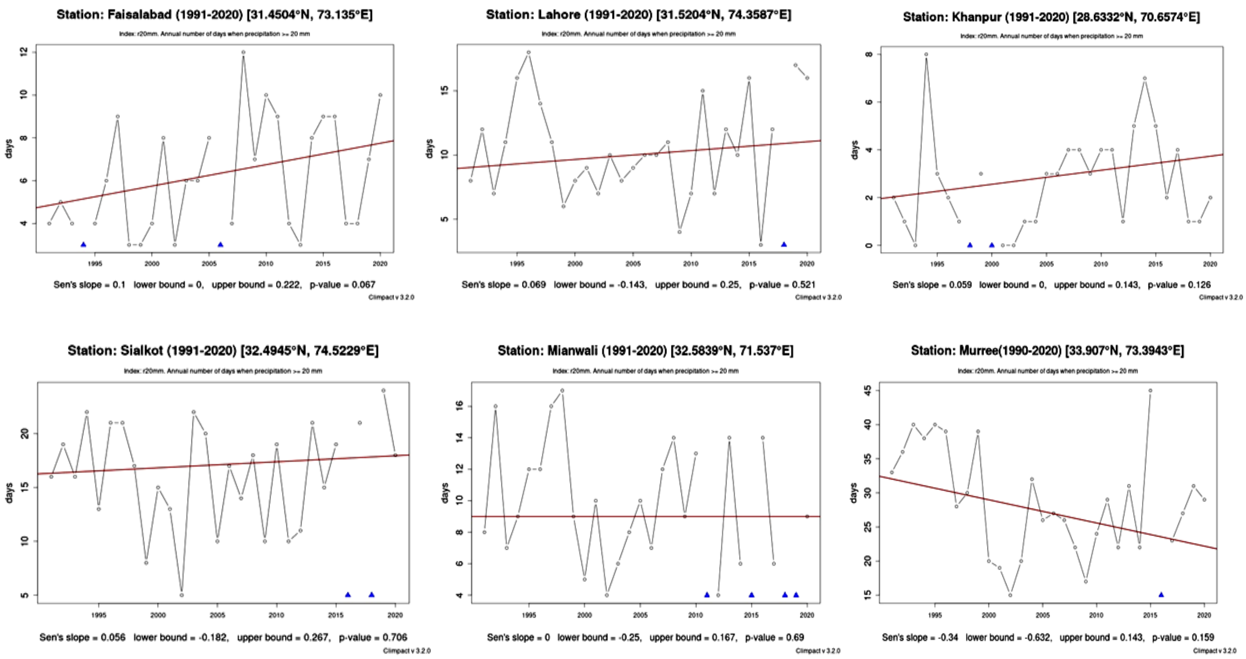


Fig. 6: R20 of six stations from 1991 to 2020.

3.2.7. R95p Indices (Annual total PRCP when RR>95th percentile): The following time series graphs (Fig. 7) illustrate the annual total days with precipitation exceeding the 90th percentile across selected stations in Punjab from 1991 to 2020. Faisalabad, Lahore, Khanpur, Sialkot, and Mianwali show a positive trend, with annual increases of 0.149%, 0.715%, 0.482%, and 0.128%, respectively. In contrast, Murree displays a negative trend, with a decrease of -14.41% in total days with precipitation above the 90th percentile annually. The trends across all stations are statistically significant, ranging from 0.01 to 0.7. The estimated average annual total days with precipitation above the 90th percentile from 1991 to 2020 are as follows: Faisalabad (95.71 days), Khanpur

(36.89 days), Lahore (173.25 days), Sialkot (269.25 days), Murree (400.89 days), and Mianwali (147.68 days). These values reflect the variability in extreme rainfall events across the region, with Murree showing a significant decline compared to other districts.

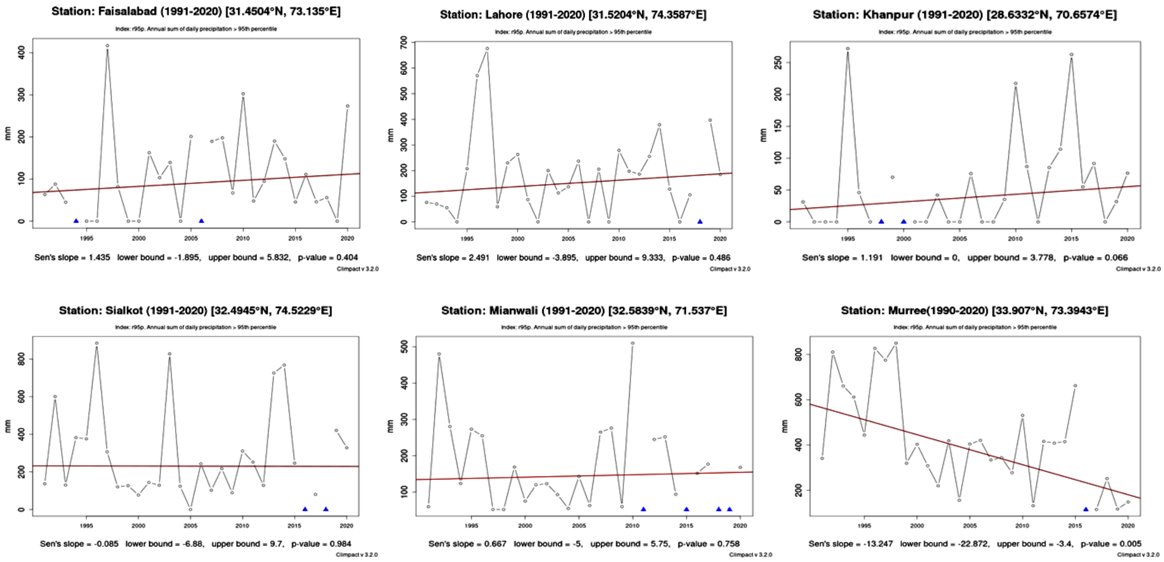
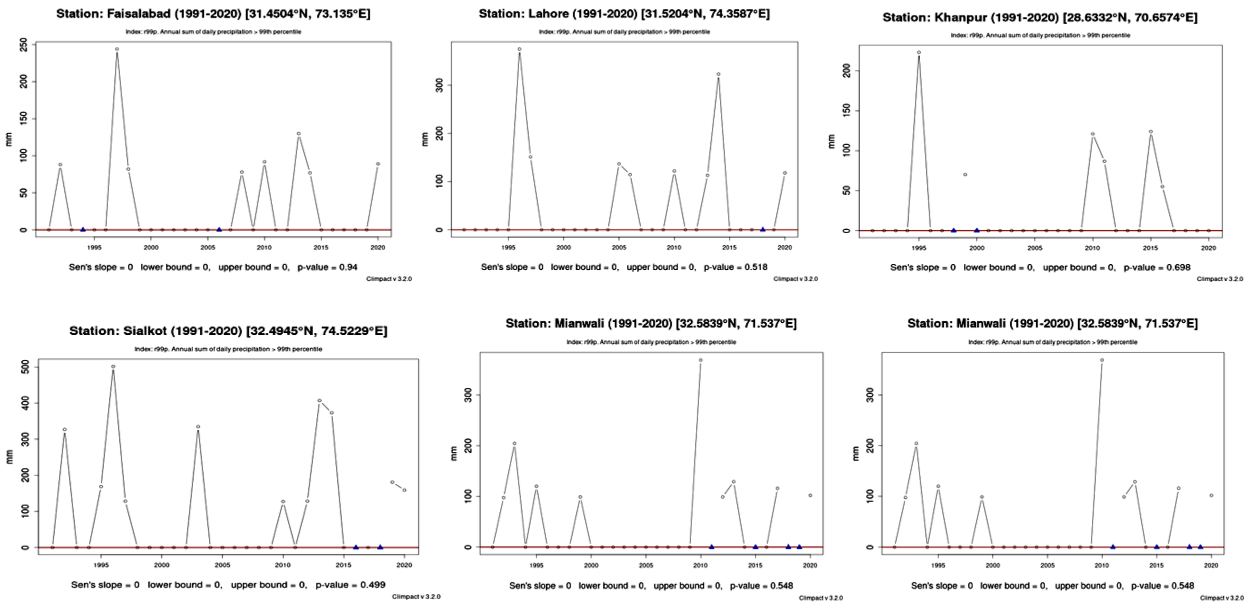


Fig. 7: R95p of six stations from 1991 to 2020.

3.2.8. R99p Indices (Annual total PRCP when RR>99th percentile): The following time series graphs in Fig. 8 depict the annual total number of days with precipitation exceeding the 99th percentile across selected stations in Punjab from 1991 to 2020. Lahore, Sialkot, and Mianwali exhibit positive trends, with annual increases of 0.778%, 0.931%, and 0.156%, respectively. Conversely, Faisalabad, Khanpur, and Murree show negative trends, with annual decreases of -0.329%, -0.277%, and -6.996% in days with precipitation above the 99th percentile. The trends across all stations are statistically significant, ranging from 0.1 to 0.8. The estimated average annual total days with precipitation exceeding the 99th percentile from 1991 to 2020 are as follows: Faisalabad (22.67 days), Khanpur (8.27 days), Lahore (45.12 days), Sialkot (87.86 days), Murree (133.46 days), and Mianwali (34.55 days). These values highlight the varying intensity of extreme rainfall events across the region.



Citation: Ameen I, Kashif M, Hameed HN and Nida H, 2024. Trend analysis of extreme weather indices in different districts of Punjab, Pakistan. Agrobiological Records 18: 29-40. https://doi.org/10.47278/journal.abr/2024.035

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
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Fig. 8: R99p of six stations from 1991 to 2020.

3.2.9. PRCPTOT Indices (Annual total PRCP in wet days (RR>=1mm)): The following time series graphs in Fig. 9 illustrate the annual total number of wet days (days with precipitation ≥1.0 mm) across selected stations in Punjab from 1991 to 2020. Faisalabad, Lahore, and Sialkot show a positive trend, with annual increases of 5.914%, 3.715%, and 2.069%, respectively. In contrast, Khanpur, Mianwali, and Murree exhibit negative trends, with declines of -0.103%, -2.57%, and -18.322% in total wet days annually. The trends across all stations are statistically significant, ranging from 0.01 to 0.9. The estimated annual sum of wet days with precipitation ≥1.0 mm during this period are as follows: Faisalabad (369.6 days), Khanpur (161.46 days), Lahore (626.11 days), Sialkot (948.57 days), Murree (1629.47 days), and Mianwali (539.18 days). These values highlight the varying precipitation patterns across different regions in Punjab.

These all-time series graphs demonstrate the annual variance between monthly maximum and minimum temperatures across selected stations in Punjab from 1991 to 2020. Sialkot shows an upward trend, with a 0.545% annual increase, signaling a positive shift. In contrast, Faisalabad, Lahore, Khanpur, Murree, and Mianwali exhibit declining trends with average variances of -0.054%, -0.023%, -0.043%, -0.067%, and -0.101%, respectively, over the monthly periods. These trends are statistically significant, falling within the range of 0 to 0.004. The study also reveals the average annual days with maximum and minimum temperature extremes during this period. Faisalabad reports an average of 13.40 days, while Khanpur shows -27.28 days, Lahore 3.90 days, Sialkot 4.17 days, Murree 6.14 days, and Mianwali -5.06 days. These values highlight the diverse temperature patterns across the region.

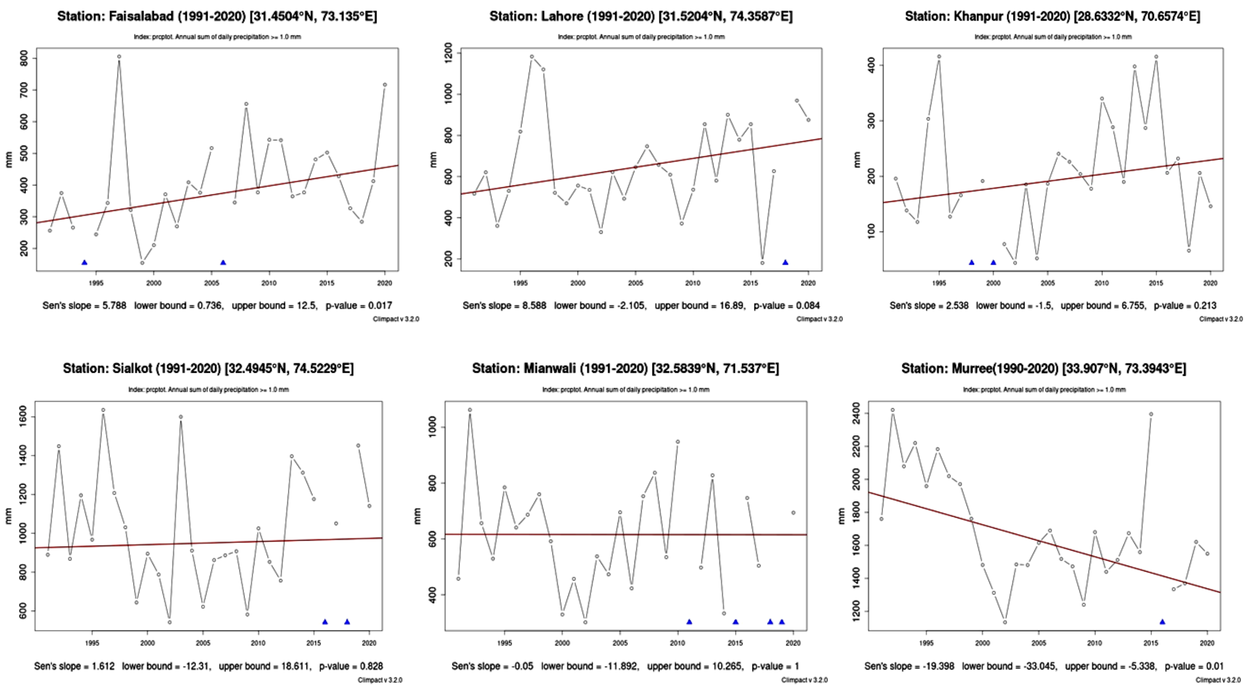

Fig. 9: PRCPTOT of six stations from 1991 to 2020.

4. CONCLUSION

As an agricultural country, Pakistan heavily depends on its agricultural sector, which is directly influenced by climate variability. This study focuses on extreme climate indices across various districts in Punjab, including Faisalabad, Lahore, Khanpur, Sialkot, Murree, and Mianwali. Data spanning 30 years on minimum and maximum temperatures and rainfall were analyzed using the RClimpact2 package of R software, which computed 22 extreme climatic indices for these locations. The study revealed different climate trends across districts. For example, Khanpur and Sialkot experienced positive trends in summer days, while Faisalabad, Lahore, Murree, and Mianwali showed negative trends. Warm spell duration also exhibited positive trends in Murree and Sialkot, whereas other districts faced negative trends. Similarly, maximum temperature trends were positive in Khanpur and Sialkot but

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
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negative in Faisalabad, Lahore, Murree, and Mianwali. The indices analyzed included such as very warm days, frost days, cold spell duration, minimum temperature days per year, diurnal temperature range, cool days, warm nights, and several rainfall metrics (e.g., RX1day, RX5day, SDII, R10, R20, CDD, CWD, R95p, R99p, PRCPTOT, TX10p, and TX90p). These indicators displayed distinct patterns across the districts, providing a comprehensive view of temperature and precipitation extremes in Punjab.

Authors' Contributions: IA and HNH collected the data and performed the statistical analysis. KM and HD prepared and edited the draft of the manuscript. All the authors were involved in the critical revision of the manuscript and approved its final version.

Acknowledgment: The authors thankful to the Pakistan Metrological Department for providing the data as required for the present research work. They also offer their gratitude to the editor and anonymous reviewers for providing valuable suggestions in order to improve the submitted article for its in-time publication.

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