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Towards Understanding Variability in Droughts in Response to Extreme Climate Conditions over the Different Agro-Ecological Zones of Pakistan

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Abstract: Here, we provided a comprehensive analysis of long-term drought and climate extreme patterns in the agro ecological zones (AEZs) of Pakistan during 1980–2019. Drought trends were investigated using the standardized precipitation evapotranspiration index (SPEI) at various timescales (SPEI-1, SPEI-3, SPEI-6, and SPEI-12). The results showed that droughts (seasonal and annual) were more persistent and severe in the southern, southwestern, southeastern, and central parts of the region. Drought exacerbated with slopes of −0.02, −0.07, −0.08, −0.01, and −0.02 per year. Drought prevailed in all AEZs in the spring season. The majority of AEZs in Pakistan's southern, middle, and southwestern regions had experienced substantial warming. The mean annual temperature minimum (Tmin) increased faster than the mean annual temperature maximum (Tmax) in all zones. Precipitation decreased in the southern, northern, central, and southwestern parts of the region. Principal component analysis (PCA) revealed a robust increase in temperature extremes with a variance of 76% and a decrease in precipitation extremes with a variance of 91% in the region. Temperature and precipitation extremes indices had a strong Pearson correlation with drought events. Higher temperatures resulted in extreme drought (dry conditions), while higher precipitation levels resulted in wetting conditions (no drought) in different AEZs. In most AEZs, drought occurrences were more responsive to precipitation. The current findings are helpful for climate mitigation strategies and specific zonal efforts are needed to alleviate the environmental and societal impacts of drought.

Keywords: SPEI; temperature extremes; precipitation extremes; PCA

1. Introduction

Drought is a recurrent natural hazard all over the world. In recent decades, frequent changes in temperature and precipitation extremes have caused growing concerns regarding drought events worldwide resulting in economic losses in the billions of dollars.

Drought events have been more serious across the world during the last 21 years [1]. In 2000, China experienced the worst drought event, which resulted in damage to 40 million hectares of crops [2]. Drought occurrences in central and northeastern India rose dramatically by the second half of the twentieth century [3]. Climate change projection under the RCP 4.5 and 8.5 scenarios indicated the significant increase in drought intensity and duration over Mexico [4]. South Asia is the most drought-influenced region in the world. In the last 55 years, Pakistan has experienced drought with a frequency of one every three years [5]. The climate of Pakistan, except for the northern part, is semiarid to hyperarid; thus, a major part of the country is highly prone to drought hazards. Most of the rain is received in December–March and July–September, while the remaining months receive less rain [6]. The economy of the country depends on agricultural products, and changes in rainfall may lead to disastrous impacts. According to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), drought is characterized as a long enough period of abnormally dry weather to cause the worst hydrological imbalancing [7]. Droughts are classified into four major categories: (a) agricultural droughts, (b) meteorological droughts, (c) socioeconomic droughts, and (d) hydrological droughts. Agricultural droughts are caused by soil moisture conditions, while meteorological droughts are caused by precipitation deficits in a particular region over a certain period [8,9]. Socioeconomic droughts occur as water shortages begin to affect people and demand for economic stakeholders [10]. Hydrological droughts, on the other hand, occur as precipitation decreases, allowing surface water levels to decrease, causing issues with normal water usage [11].

Certain commonly used meteorological indices include the crop moisture index (CMI) [12], the standardized precipitation index (SPI) [13], the standardized precipitation evapotranspiration index (SPEI) [14], and the water surplus variability index (WSVI) [15]. Global warming and the El Niño phenomenon destabilize the atmospheric structure and the ocean monsoons, consequently increasing drought events across the globe, including in North America, East Africa, East Asia, and Australia [16–19]. Around the world, arid and semiarid regions including North Africa, India, North China, the Middle East, Mexico, Middle Asia, Australia, Canada, southwestern Europe, and the western United States have faced the worst drought disasters [20]. Sheffield and Wood (2008) concluded that long-term persistent droughts have increased threefold globally [21]. Droughts are very common in the Greater Horn of Africa (GHA), which has an arid and semiarid climate [22,23]. In recent years, the GHA has faced increased drought frequency and duration [24,25]. Asia is also extremely vulnerable to drought, and East and Southeast Asia are highly influenced by drought disasters due to the large population and monsoon climate [11,26,27]. The monsoon climate system in the region of Southeast Asia defines climates (e.g., precipitation, temperature, evaporation, wind direction); drought occurrence and characteristics depend on it [28,29]. The different climate zones within Asia show the regional differences in monsoon climate features [30]. Seventy to ninety percent of the area of Pakistan has arid to semiarid climate, and this area has diverse geography [31,32]. In the past, the intensity, frequency, and occurrence of climatic events have been increased. About 40% of people in Pakistan are prone to multiple disasters, including droughts. During the summer and winter seasons, Pakistan receives a lot of rain from the southwest monsoon. Different extreme events were observed in Pakistan during the year 2015. The Baluchistan province of Pakistan has the most pronounced drought events due to its arid climate and weak adaptiveness [6]. The SPI [33] showed a negative trend in Baluchistan from 1975 to 2010 [34]. A study that used SPEI found that the Baluchistan region had a negative SPEI value, indicating the intensified drought during 1902–2015 [35]. Ghani et al. (2018) concluded that SPI exhibited a significant negative trend in Balakot and a positive trend in Parachinar using met station data [36]. The worst heat wave was observed in the Sindh province during 17–24 June 2015, killing over 1200 people in the provincial capital city of Karachi. In recent years, climate change extremes have wreaked havoc on regional environmental conditions [37]. The central and southern parts of Pakistan faced highly frequent drought spells because of interannual rainfall variability and higher temperature [38,39]. The strength of La Niña phases has increased the intensity of high-temperature events in the arid and semi-arid climate zones of Pakistan [27]. El Niño–Southern Oscillation (ENSO) affected the Hadley cell and induced significant changes over South Asian monsoon rainfall patterns [40]. Iqbal and Athar (2018) concluded that monthly Indian Ocean dipole (IOD) has strongly impacted the precipitation cycle in Baluchistan, Pakistan. Moreover, the Atlantic Multidecadal Oscillation (AMO) had a moderate correlation, and ENSO had a strong correlation, with precipitation on annual basis [41]. The positive phase of El Niño and La Niña has a significant impact on South Asian countries [42]. Understanding long-term drought variability is significant for increasing resilience capability to future droughts. A comprehensive drought monitoring system is vital for developing regional drought strategies and policies [43]. An efficient early warning of drought persistence, severity, and onset can be attained by long-term drought information. To this end, it is important for water resource management to study historical drought SPEI time series at the regional level. Recently, a study was conducted on regional changes in temperature extremes and their relation to Pacific variability in the AEZs of Pakistan [44]. The trend and variability of temperature and precipitation extremes, as well as their impact on drought variability in AEZs, are still unknown. To fulfill this gap, the current study investigated the long-term trend of drought and climate extremes on annual and seasonal timescales in AEZs. The influence of climate extremes on drought variability was explored in the different climate zones of Pakistan. The temperature and precipitation trends are not consistent across the region, and different sectors of society need to be adaptive to climate extremes.

In the current study, there were three main objectives. The first was to understand the long-term variability of climate extremes (temperature and precipitation) in AEZs of Pakistan from 1980 to 2019. The second was to examine long-term patterns of drought duration, frequency, and intensity regarding historical drought assessment in AEZs of Pakistan over the past 40 years (1980–2019). We used the SPEI, which was made to investigate the changes of droughts under global warming. The SPEI has benefits in assessing droughts caused by evapotranspiration [45,46]. The SPEI has the combined advantages of the SPI [13] and the Palmer drought severity index (PDSI) [12]. Consequently, drought indices were used to quantify droughts, as they provide a comprehensive delineation of droughts as well as drought characteristics including frequency, intensity, and duration [47]. The third objective was to explore the temporal variation of the long-term drought cycle in relation to climate extremes in Pakistan.

The results of this study will help to understand the relationship between droughts and climate extreme changes over AEZs, as well as in developing mitigation strategies for droughts' impact in the region. This manuscript is arranged in the following sections. The data and methodology are explained in Section 2, while results and discussion are described in Sections 3 and 4, respectively.

2. Materials and Methods

2.1. Study Area

The present study is conducted in Pakistan, a country north of the equator with a geographical location between the latitudes of 23 and 37° North and the longitudes of 60 and 77° East that covers an area of 79.6 billion hectares. Pakistan was divided into four major climate zones, namely glacial, humid, arid, and extremely arid regions [38]. The northern part is mainly covered with glaciers and snow at a mean altitude of 4158 m.a.s.l. The humid region consists of the Himalaya, Karakoram, and Hindukush ranges, which receive mean rainfall of 825 mm per year at an elevation of 1286 m.a.s.l. The central arid region is characterized by low plains and has main agricultural areas, with average rainfall and altitude of 322 mm per year and 633 m.a.s.l, respectively. Finally, the zones at the southern boundary along the Arabian Sea (particularly the Western Dry Plateau and the Indus delta) are extremely arid; the region gets 133 mm mean rainfall per year, with a bare soil region at an average altitude of 444 m.a.s.l. and variant mountain ranges (low, high, and dry) [48]. The current study focuses on 10 different AEZs, based on climate, agricultural, and geographical conditions as classified by [49] and shown in Figure 1, and each zone's changing climate constraints to a greater extent as shown in Table 1.

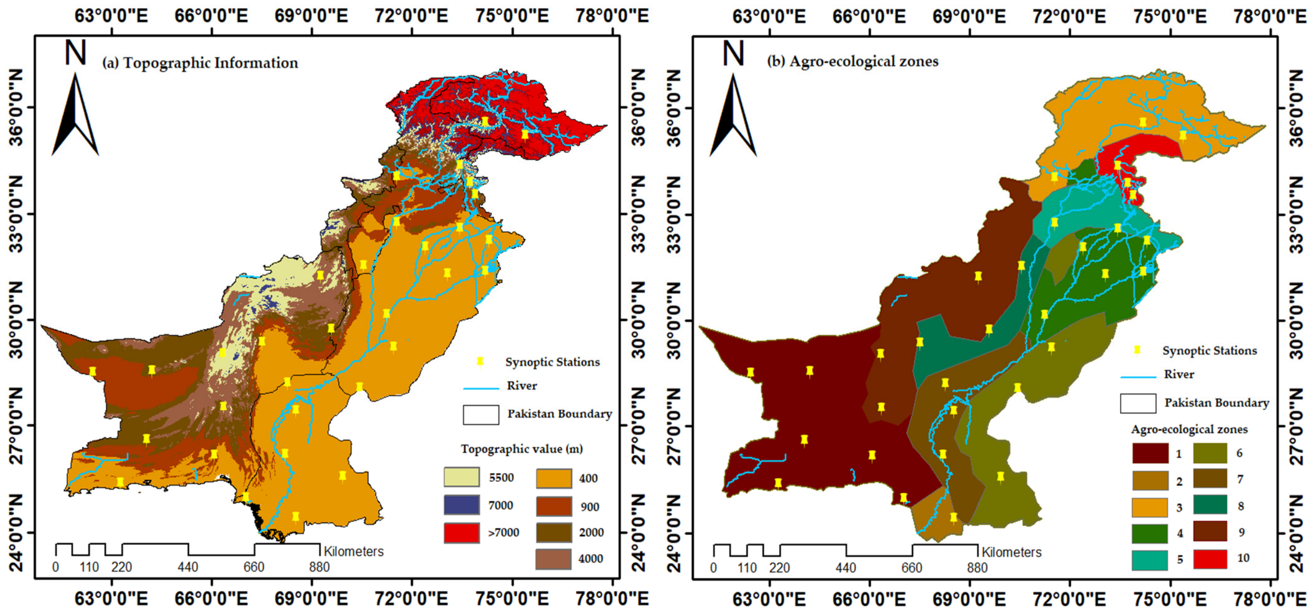

Figure 1. Study area with (**a**) topographic information (meter) and (**b**) agro-ecological zones (AEZs) information. Zone explanation: dry western plateau[1], Indus delta[2], northern dry mountains[3], northern irrigated[4], rainfall[5], sandy desert[6], southern irrigated[7], Suleiman pieomont[8], western dry mountain[9], and wet mountains[10].

Table 1. Detailed description of AEZs of Pakistan.

Zones	Rainfall (mm/day)	T_{max} (°C/day)	T_{min} (°C/day)	Climate	Crops
Dry Western Plateau[1]	1.3 mm	32 °C	18 °C	Arid tropical marine	Wild olives, small trees, grasses
Indus delta[2]	1.4 mm	33 °C	21 °C	Arid tropical marine	Sugarcane, cotton, wheat
Northern dry mountains[3]	4.0 mm	24 °C	10 °C	Sub humid	Grazing pattern
Northern irrigated[4]	4.6 mm	32 °C	17 °C	Semi arid	Wheat, cotton, millet, rice, mangoes, citrus
Rainfall[5]	9.8 mm	30 °C	16 °C	Sub humid	Rice, wheat, maize, mustard, and barley
Sandy desert[6]	2.4 mm	33 °C	18 °C	Arid	Shrubs, grasses
Southern irrigated[7]	1.4 mm	35 °C	19 °C	Arid subtropical	Cotton, wheat, berseem, and sorghum
Suleiman Piedmont[8]	2.4 mm	33 °C	18 °C	Arid subtropical	Millet, wheat
Western Dry Mountains[9]	5.4 mm	25 °C	10 °C	Semi arid	Apple, peach, apricot, grapes, plum
Wetmountain[10]	16.7 mm	26 °C	13 °C	Humid	Wheat, maize

2.2. Data Collection and Processing

The current study uses ground-based observations. To ensure data quality, the most up-to-date and completed record stations were chosen for the current study. Daily time series data of precipitation and temperature (maximum, minimum) from 1980 to 2019 was obtained from the Pakistan Meteorological Department (PMD). Meteorological data for the 32 stations were spatially distributed over the study area and covered each AEZ, as shown in Table 2. Each zone has a different number of climate stations and was averaged to represent the drought characteristics of a zone. Each zone represents the spatial characteristics of drought events (duration, frequency, and intensity). Moreover, to explore the relationship between climate extremes (temperature and precipitation) and drought in the different AEZs in Pakistan, we used different indices.

Table 2. Met station information in different AEZs of Pakistan.

Station Name	Latitude	Longitude	Elevation (m)	Station Name	Latitude	Longitude	Elevation (m)
Dalbandin	28°53′ N	64°24′ E	848 m	Bahawal Pur	29°20′N	71°47′ E	110.00 m
Nokkundi	28°49′ N	62°45′ E	682 m	Rahim Yar Khan	28°26′ N	70°19′ E	82.93 m
Panjgur	26°58′ N	64°06′ E	968 m	Chhor	29°53′ N	69°43′ E	5 m
Pasni	25°16′ N	63°29′ E	9 m	Jacobabad	28°18′ N	68°28′ E	55 m
Karachi	24°54′ N	66°56′ E	22 m	Nawabshah	26°15′ N	68°22′ E	37 m
Peshawar	34°02′ N	71°.56′ E	327 m	Rohri	27°40′ N	68°54′ E	66 m
Gilgit	35°55′ N	74°20′ E	1460 m	Badin	24°38′ N	68°54′ E	9 m
Skardu	35°18′ N	75°41′ E	2317 m	Barkhan	29°53′ N	69°43′ E	1097 m
Bahawal Pur	29°20′ N	71°47′ E	110.00 m	Sibbi	29°33′ N	67°53′ E	133 m
Sargodha	32°3′ N	72°40′ E	187 m	D.I. Khan	31°49′ N	70°56′ E	171.20 m
Faisalabad	31°26′ N	73°08′ E	185.6 m	Kalat	29°2′ N	66°35′ E	2015 m
Multan	30°12′ N	71°26′ E	121.95 m	Khuzdar	27°50′ N	66°38′ E	1231 m
Lahore PBO	31°33′ N	74°20′ E	214.00 m	Kotli	33°31′ N	73°54′ E	614.0 m
Jhelum	32°56′ N	73°44′ E	287.19 m	Rawalakot	33°52′ N	73°41′ E	1677.0 m
Mianwali	32°71′ N	71°55′ E	———	Muzaffarabad	34°22′ N	73°29′ E	702.0 m
Sialkot	32°31′ N	74°32′ E	255.1 m	Zhob	31°21′ N	69°28′ E	1405 m

2.3. *Quantification of Droughts*

In the present study, data collected from reanalysis (ERA5) and in situ observation were used to quantify metrological and hydrological droughts over the different agro-ecological settings in Pakistan.

2.3.1. Metrological Drought Conditions

SPEI was used as an indicator of metrological extremes in the study region. The SPEI uses precipitation (P_i) and potential evapotranspiration (PET_i) in its drought calculation. P_i and PET_i were used to calculate the monthly water balance (WB_i);

$$WB_i = P_i - PET_i \tag{1}$$

PET was calculated using the Hargreaves method due to the limitation of climate parameters. After calculating WB_i at each station, the results were passed through the SPEI R package to calculate the SPEI at multiple timescales, such as 1 month (SPEI-1), 3 months (SPEI-3), 6 months (SPEI-6), and 12 months (SPEI-12) (http://cran.r-project.org/web/packages/SPEI). The multiple time series of the SPEIs were obtained as SPEI-1, SPEI-3, SPEI-6, and SPEI-12 using Equation (2):

$$f(x) = \left[1 + \left(\frac{a}{x-\gamma}\right)^{\beta}\right]^{-1} \tag{2}$$

where α, β, and γ are the scale, shape, and origin parameters, respectively.

$$SPEI = W - \frac{C_0 + CW^1 + CW^2}{1 + d_1 w + d_2 w^2 + d_3 w^3} \quad \mathrm{w} = \sqrt{-2\mathrm{In}(\mathrm{p})} \tag{3}$$

When $p \leq 0.5$, $p = 1 - f(x)$; when $p > 0.5$, $p = 1 - p$, and the sign of the SPEI is reversed. The constants are $c_0 = 2.515517$, $c_1 = 0.802853$, $c_3 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$ and $d_3 = 0.001308$. The regional SPEI in each AEZ was obtained by averaging SPEI values for all climate stations scattered in that zone. The SPEI time series give positive and negative values that represent wet and dry conditions. The threshold value of −1 (SPEI ≤ −1) was used to determine the drought condition [50]. For annual and seasonal drought analysis, SPEI-12 and -3 were considered in the present study.

2.3.2. Drought Characteristic Analysis

Drought conditions, such as frequency, duration, intensity, and severity, explain drought characteristics [51]. Drought characteristics were understood by a probabilistic method known as the theory of run [52]. The drought duration, frequency, and intensity of SPEI time series data were calculated using the theory of run method in the different AEZs of Pakistan. Drought was identified by SPEI values below the threshold value (−1) [53,54]. More negative values < −1 showed severe drought conditions as compared to long-term conditions. The more negative the threshold value, the worse the drought [53]. The SPEI value below the threshold value (−1) indicates the lack of rain as compared to atmospheric water. Drought properties, including frequency, duration, and intensity, were calculated for each drought event during the last 40 years in Pakistan.

Drought Duration

Drought duration was defined as the length of time between the start and termination of a drought (the number of months) [33,55]. It can be calculated by the sum of durations for all drought events that occurred divided by the number of drought events, as written [53]:

$$D = \frac{\sum_{i=1}^{n}(d_i)}{n} \tag{4}$$

where d_i is the duration of the ith event in an area and n is the number of drought events in the region.

Drought Frequency

Drought frequency is the number of drought events in a certain period [2]. It is the ratio between the number of drought months and the total number of months in the time series [56]:

$$F = \frac{n_m}{N_m} \times 100\% \tag{5}$$

where F is the drought frequency, n_m the number of drought months, and N_m is the total number of months (40 × 12 = 480).

Drought Intensity

Drought intensity is also another important factor. Drought intensity counts drought severity level according to drought duration, which is quite helpful for determining the magnitude of droughts [57]. It is the absolute average of accumulated SPEI values during drought conditions [56]. Drought severity measures the cumulative deficit below the truncation level to assess drought intensity [57]. The estimation of drought intensity helps to detect how intensified drought may lead to drying the environment:

$$\mathrm{I} = \left| \frac{1}{n} \sum_{i=1}^{n} (SPEI_i) \right| \tag{6}$$

where I is the drought intensity, n is the number of drought occurrences, and $SPEI_i$ is the accumulated SPEI value below the threshold for drought event i.

2.4. Quantification of Climate Extreme Indices

Precipitation and temperature extremes analyses were performed using the RClimDex software in RStudio for data from 1980 to 2019. For the calculation of monthly and annual indices, we used threshold conditions where no more than 2 days were absent from a month and where no more than 10 days were absent from a year. Furthermore, if any month had no data, no yearly value was calculated for the year containing that month. This paper found the trends annually and seasonally for the precipitation and temperature indices; a detail description is in Table 3.

Table 3. Definition of extreme temperature and precipitation indices.

Indices	Name	Description	Unit
Mean Tmax	Annual mean maximum temperature	Annual mean maximum temperature	°C
Mean Tmin	Annual mean minimum temperature	Annual mean minimum temperature	°C
TXx	Annual daily maximum temperature	Annual maxima value of daily maximum temperature	°C
WSDI	Warm spell duration	Annual number of days with at least 6 consecutive days when Tmax > 90th percentile	day
DTR	Diurnal temperature	Annual mean difference between daily max and min temperature	°C
PRCPTOT	Total precipitation	Annual precipitation from day ≥ 1 mm	mm
R10	Heavy precipitation	Annual count when precipitation ≥ 10 mm	day
R20	Very heavy precipitation	Annual count when precipitation ≥ 20 mm	day
Rnn	Extremely heavy precipitation	Annual count when precipitation ≥ 25 mm	day
R95p	Very wet days	Annual total precipitation from days >95th percentile	mm
R99p	Extremely wet days	Annual total precipitation from days >99th percentile	mm
RX1	1-day precipitation	Annual maximum 1-day precipitation	mm
RX5	Consecutive 5-day precipitation	Annual maximum consecutive 5-day precipitation	mm

2.5. Drought Trend Analysis

The aforementioned SPEI and climate extreme indices were evaluated to detect the trends and their magnitude using two methods; a nonparametric Mann–Kendall (MK) test [58,59] and Sen's slope were computed for the monotonic positive and negative magnitude of trends to determine the slope value [60] to evaluate the trend changes in drought in Pakistan. The trend values for the total stations in a zone were averaged to calculate zonal trends (Tables 5 and 6). The MK test was used for the inhomogeneous time series data and has low sensitivity to data. To illustrate the temporal pattern in the SPEI time series, the Z_{mk} test statistic was used (the Z_{mk} test was described in detail in [58,59]). The mathematical equations to calculate Mann–Kendell statistics $V(S)$, S, and standardized test statistics Z are given as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sig\left(X_j - X_i\right),$$

$$sgn\left(X_j - X_i\right) = \begin{cases} +1, & if \ \left(X_j - X_i\right) > 0 \\ 0 & if \ \left(X_j - X_i\right) = 0 \\ -1 & if \ \left(X_j - X_i\right) < 0, \end{cases}$$

$$V\ (S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p\left(t_p - 1\right)\left(2t_p + 5\right)\right], \quad (7)$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & if \ S > 0 \\ 0 & if \ S = 0 \\ \frac{S-1}{\sqrt{VAR(S)}} & if \ S < 0, \end{cases}$$

In the above equations, X_i and X_j are the observations in chronological order, n is length of time, tp is the tied values for the pth value, and q is the number of tied values. In our study, the significance of trend was tested at the Z-critical value of 1.96 with a significance level of 0.05. The null hypothesis of no trend must satisfy the condition if $-1.96 > Z_{mk} > 1.96$.

Sen's Slope Estimation

Sen's slope was estimated using Sen's nonparametric method to determine the magnitude of trends of time series data:

$$T_i = \frac{X_j - X_k}{j - k} \tag{8}$$

In the equation, X_j and X_k represent data values at time j and k, respectively. Consider:

$$Q_i = \begin{cases} T_{\frac{(N+1)}{2}} & N \text{ is odd} \\ \frac{1}{2}\left(T_{\frac{(N)}{2}} + T_{\frac{(N+2)}{2}}\right) & N \text{ is even,} \end{cases} \tag{9}$$

where positive values of Q_i show an increasing trend, while negative values show a decreasing trend over time.

2.6. Principal Component Analysis (PCA)

Principal component analysis (PCA) is the oldest technique of multivariate statistical data analysis approach that explains the variability in data. It segregates a set of variables into principal factors through a linear transformation process [61]. Pearson (1901) first invented it, and it was developed further by Hoteling (1933) [62,63]. PCA is a general name for a technique that uses sophisticated underlying mathematical principles to transform several possibly correlated variables into a set of a smaller number of orthogonal variables known as principal components. It depends on the eigendecomposition of semidefinite matrices and the singular value decomposition (SVM) of rectangular matrices. This method finds the less important variables and solves the problem of too few or excessive selections, which alters the accuracy of the research process. The main idea of PCA is to reduce the dimensionality of data when it has a large number of interrelated variables, to retain possible variation in the data. Further detailed mathematical expressions for calculation are given in Gao (2015) [64]. In recent years, many researchers have used PCA for regional climate studies [43,65,66]. It also provides original information of data by keeping the parameters independent of one another [65]. We used the PCA method to study the features of extreme temperature and precipitation indices in order to explore the variability in extreme temperature and precipitation indices in the different AEZs over the last 40 years. It identified the variances in climate extremes.

3. Results

3.1. Drought Characteristics Analysis

3.1.1. Drought Duration

Drought duration is an important property of drought. Figure 2 illustrates the mean duration of drought at different AEZs over Pakistan from 1980 to 2019. The drought duration of SPEI-1 was higher in all zones except zone[10]. The maximum drought duration of SPEI-1 was 5 months and the minimum was 3.5 months in zones[1,10], respectively. The drought duration of SPEI-3 was higher in all zones except zone[3]. The maximum drought duration for SPEI-3 was 5.4 months and the minimum was 3.8 months in zones[10,3], respectively. For SPEI-6, the drought duration was shorter than that of SPEI-1 and SPEI-3 except in zone[3]. The maximum drought duration was 4.3 months and the minimum was 3.55 months in zones[3,6], respectively. For SPEI-12, the maximum drought duration was 4.1 months and the minimum was 3.1 in zones[3,2], respectively. In Pakistan, the mean drought duration was 4.3, 4.1, 3.8, and 3.7 months for SPEI-1, SPEI-3, SPEI-6, and SPEI-12, respectively. Drought duration continued to decrease as the SPEI timescale increased. Droughts identified based on SPEI-1 and SPEI-3 persisted for a longer time than those identified based on SPEI-6 and SPEI-12. Drought duration decreased with the time scale, and droughts at SPEI-1 tended to last longer than those at SPEI-12. Wide drought duration values indicated prolonged droughts over a longer time, while the smaller-scale duration values showed frequent but short-term droughts.

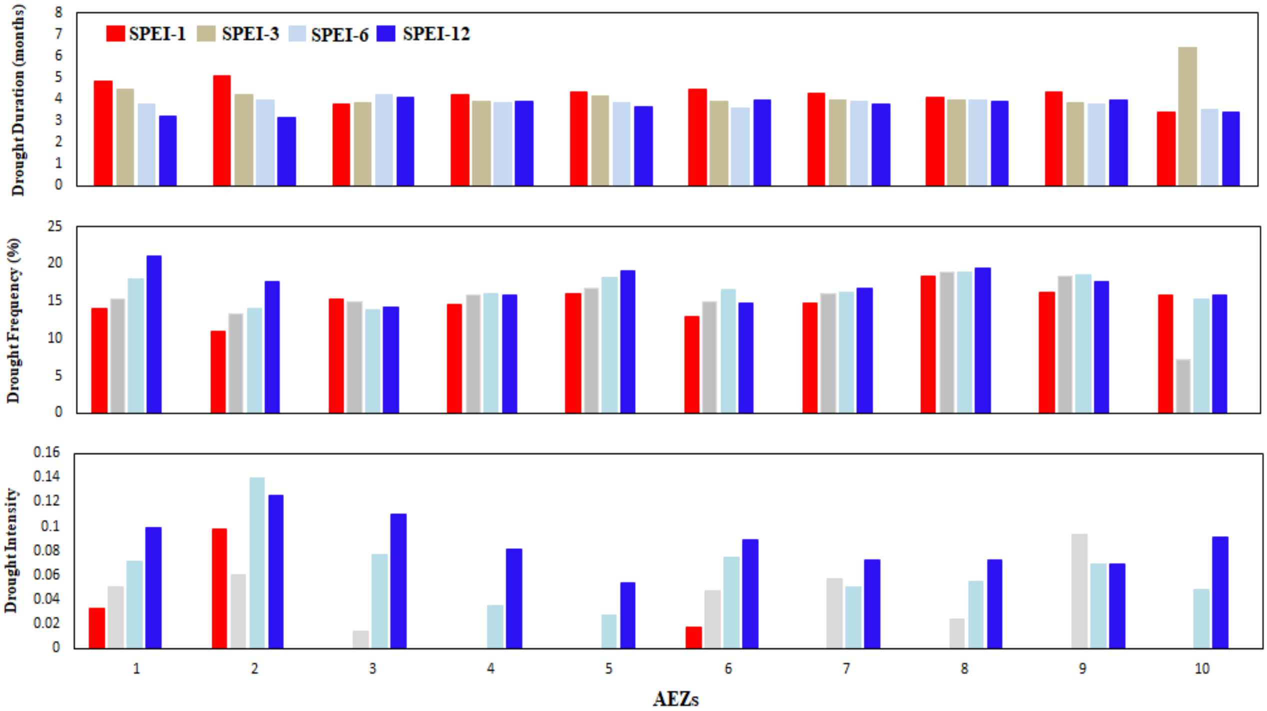

Figure 2. SPEI drought duration, drought frequency, and drought intensity over agro-ecological zones (AEZs) of Pakistan.

3.1.2. Drought Frequency Analysis

Drought frequency is a major factor in demonstrating the distinct behavior of SPEI in AEZs across Pakistan over the past 40 years. It is elucidated that the drought frequency is expected to increase with SPEI timescale. The average drought frequency for SPEI-12 was higher than that for SPEI-1 in all AEZs over Pakistan during 1980–2019. Zones^{2,8} had the highest and lowest drought frequencies, with magnitudes of 18.4% and 11%, respectively, for SPEI-1. The highest and lowest SPEI-3 frequencies were 19% and 7.2% in zones^{2,10}, respectively. The drought frequency of SPEI-6 was highest in zone_1 and lowest in zone^{3} with magnitudes of 17.9% and 13.7%, respectively. For SPEI-12, the maximum drought frequency was 22% and the minimum was 14.5% in zones_1,3, respectively. The mean drought frequency was 14.8%, 15.1%, 16.5%, and 17.2% for SPEI-1, SPEI-3, SPEI-6, and SPEI-12, respectively, over the Pakistan region. Generally, drought frequency at large SPEI scales (SPEI-6, -12) persisted more than that at short SPEI scales (SPEI-1, -3) [67].

3.1.3. Drought Intensity Analysis

Drought intensity explained the consistency of drought in various AEZs across Pakistan from 1980 to 2019. The highest drought intensity was in zone^{2} for all of the SPEI timescales, while the lowest drought intensity was found in zone^{5}. The mean drought intensity over Pakistan was 0.01, 0.03, 0.06, and 0.08 for the timescales SPEI-1, SPEI-3, SPEI-6, and SPEI-12, respectively. Drought intensity for SPEI-12 had a maximum value of 0.12 and a minimum value of 0.05 in zones^{2,5}, respectively. Similarly, intensity for SPEI-6 had a maximum value of 0.14 and a minimum value of 0.03 in zones^{2,5}, respectively. Drought intensity for SPEI-3 was zero in three zones (namely zones^{4,5,10}), but it was highest in zone^{2} with a value of 0.06. For SPEI-1, drought intensity had a maximum of 0.1 and a minimum of 0. It can be observed in Figure 2 that drought intensity tended to increase with timescale and that different timescales showed variation in drought intensity. The southern part of the region experienced a high-intensity drought.

3.2. Long-Term Annual Drought Variations

Figure 3 represents the variation of SPEI drought in Pakistan's different AEZs from 1980 to 2019. Drought increased in all AEZs after 2000. The SPEI time series showed the increasing drought trend. It was evident that the droughts of 1980–1990 and 2000–2019 were more serious than those of the rest of the period. Droughts of varying intensity occurred more often during the study period. For example, the severe drought in all AEZs from 2000 to 2005 was caused by the rainfall decline after 2000 in Pakistan. During 1995–2013, a decreasing trend of rainfall was found in a study by Iqbal [41]. According to the study results of Jamro [68], the northern part of Baluchistan faced more frequent but shorter droughts with average severity. The summer dry period caused by scarcity of monsoon precipitation caused a reduction of productivity by affecting the province's agriculture [69].

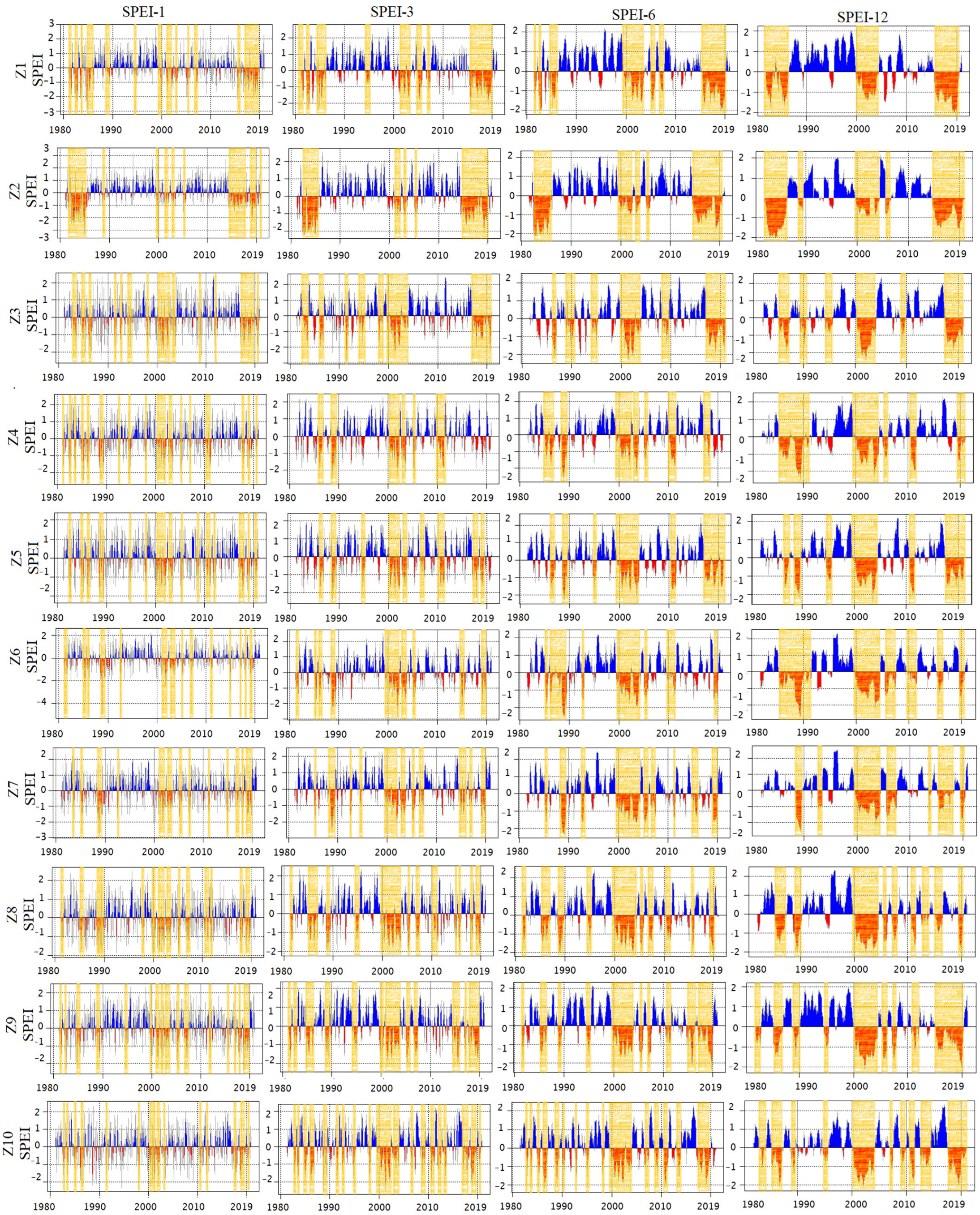

Figure 3. Long-term SPEI trend over all AEZs for the period 1980–2019. Note: Orange shaded bands highlight prominent drought events. Each zone has different climate stations that were averaged for analysis.

Long-Term Seasonal Drought Variations

Figure 4 and Table 4 describe the seasonal (SPEI-3) time series of drought from 1980 to 2019. The patterns of seasonal drought variation followed the same patterns through timescales, but higher frequency over a shorter period. For example, in zone^{1}, seasonal drought has been more severe in all seasons since 2015. During the period 1981–1983, spring and autumn and after 2015 spring, winter as well as autumn experienced the bad drought condition in zone^{2}. The drought values were more negative after 2000–2005 but during 1991–1997 drought values were positive showed no drought in zone^{6,9} in all seasons. In general, all zones are experiencing drought conditions during the study period 1980–2019. The seasonal drought captured the wetting trend during 1991–1997 and the drying trend during 2000–2005 in zone^{6,9} well.

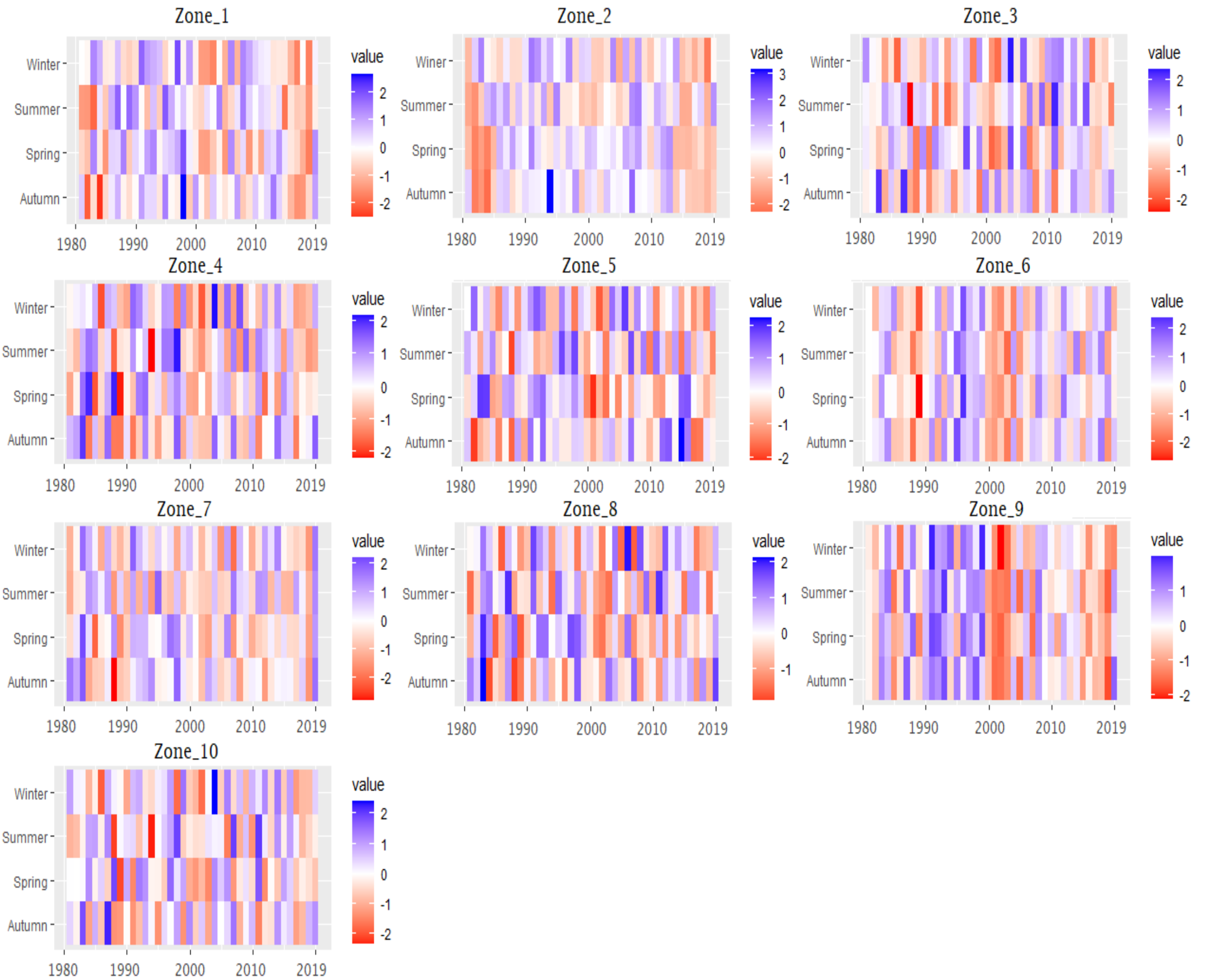

Figure 4. Seasonal trend of drought based on SPEI-3 (winter, summer, spring, and autumn) for the period 1980–2019.

Table 4. Mean annual and seasonal trend of SPEI-12 and -3 in different agro-ecological zones in Pakistan. Season description: winter = Nov + Dec + Jan, spring = Feb + March + April, summer = May + June + July, autumn = Aug + Sep + Oct.

Index	Season/Annual	Zone_1	Zone_2	Zone_3	Zone_4	Zone_5	Zone_6	Zone_7	Zone_8	Zone_9	Zone_10
SPEI	Winter	-2.00^{M*}	-1.99^{M*}	0.66^{M}	-0.31^{M}	-1.08^{M}	0.47^{M}	-0.43^{M}	-0.33^{M}	-1.98^{M*}	0.05^{M}
		-0.02^{S}	-0.02^{S}	0.08^{S}	-0.00^{S}	-0.01^{S}	0.06^{S}	-0.00^{S}	-0.06^{S}	-0.02^{S}	0.01^{S}
	Spring	-1.17^{M}	0.05^{M}	-0.03^{M}	-0.75^{M}	-1.54^{M}	0.26^{M}	-1.15^{M}	-0.94^{M}	-1.40^{M}	-1.13^{M}
		-0.05^{S}	0.00^{S}	-0.00^{S}	-0.01^{S}	-0.02^{S}	0.06^{S}	-0.01^{S}	-0.01^{S}	-0.01^{S}	-0.01^{S}
	Summer	-0.80^{M}	0.33^{M}	-0.15^{M}	-1.03^{M}	-0.52^{M}	0.59^{M}	0.40^{M}	-0.15^{M}	-1.97^{M*}	0.22^{M}
		-0.01^{S}	0.00^{S}	-0.00^{S}	-0.01^{S}	-0.06^{S}	0.06^{S}	0.05^{S}	-0.00^{S}	-0.02^{S}	0.00^{S}
	Autumn	0.08^{M}	-0.71^{M}	0.96^{M}	0.54^{M}	1.24^{M}	0.33^{M}	-0.45^{M}	0.87^{M}	-1.61^{M}	0.57^{M}
		0.00^{S}	-0.01^{S}	0.01^{S}	0.00^{S}	0.01^{S}	0.04^{S}	-0.00^{S}	0.01^{S}	-0.00^{S}	0.08^{S}
	Annual	-1.33^{M}	-0.50^{M}	-0.26^{M}	0.73^{M}	-0.75^{M}	0.80^{M}	-0.24^{M}	-0.61^{M}	-1.98^{M*}	-0.26^{M}
		-0.01^{S}	-0.00^{S}	0.00^{S}	0.01^{S}	-0.01^{S}	0.01^{S}	-0.00^{S}	-0.00^{S}	-0.02^{S}	-0.00^{S}

Note: * shows significance at $p = 0.05$. ^{M} means Mann–Kendall trend, and ^{S} means Sen slope. Red = increasing and blue = decreasing.

3.3. Long-Term Trends in Temperature Indices

Temperature indices revealed the increasing trend of warming in all AEZs during the period 1980–2019 in Pakistan. Table 5 shows the pattern of trends in warming across Pakistan. On an annual scale, the mean Tmin increased significantly more than Tmax in all zones. The regional mean Tmax (Tmin) was calculated to be 4.13 (4.33), 4.05 (4.48), 4.38 (4.89), −0.83 (4.21), −0.83 (4.21), −1.13 (4.26), −1.51 (3.42), 1.97(4.18), 3.37 (3.78), and 3.54 (5.27) in zones[1,2,3,4,5,6,7,8,9,10], respectively. The mean Tmax increased in all zones except zones[4,5,6,7], while a significant trend was found in zones[1,2,3,8,9,10]. The mean Tmin positively increased in all AEZs, and a significant trend was observed in all zones except zone[5]. An increasing trend of the number of hot days (TXx) was revealed in all zones except zones[4,6,7]. Diurnal temperature (DTR) decreased because of the mean Tmin increasing trend and found a significant trend in zones[1,4,5,6,7,10]. The warm spell (WSDI) increased during the 40 years in all zones, with a maximum increase in zone[1]. The number of summer days (SU) with increasing and decreasing trends were calculated in different AEZs over Pakistan. There was a decreasing trend of SU with a range of −0.24 to −1.98 in zones[5,6,7,8]. As shown in Table 6, the seasonal analysis, spring had an increasing trend in mean Tmax except in zone[1], and significant increasing and decreasing trends were calculated in autumn for most of the zones. For mean Tmin, a general increasing trend in all seasons was observed, and during the spring and autumn, a significant increasing trend with the ranges 2.02–4.18 and 3.14–5.63 was calculated in all zones. During winter and spring, TXx had an increasing trend. Spring and autumn showed a significant trend of TXx in all zones except zone[2,7,9] and zone[6,7,8,10], respectively. The fluctuating trend of mean Tmax is visible in autumn, while mean Tmin increased in all seasons, but a higher magnitude of mean Tmin was observed in autumn. According to TXx, all zones experienced significant changes during spring, summer, and autumn. Overall, warming intensified in all zones as the mean Tmin increased. Figure 5 generally shows the increasing trend in temperature extreme indices computed for Pakistan from 1980 to 2019. The DTR showed a negative trend during summer and autumn and a fluctuating trend in the winter and spring. A significant negative trend was calculated in most the zones except for zones[1,9], which mainly shows that mean Tmin raised during the autumn season.

Table 5. Mean annual trend of extreme temperature and precipitation indices in different agro-ecological zones in Pakistan. Note: * shows significance at p = 0.05. ^{M} means Mann–Kendall trend, and ^{S} means Sen slope.

Extreme Indices	Indices Details	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone_6	Zone 7	Zone 8	Zone 9	Zone 10
Temperature indices	Mean Tmax	4.13 ^{M*}	4.05 ^{M*}	4.38 ^{M*}	−0.83 ^{M}	−0.83 ^{M}	−1.13 ^{M}	−1.51 ^{M}	1.97 ^{M*}	3.37 ^{M*}	3.54 ^{M*}
		0.04 ^{S}	0.02 ^{S}	0.04 ^{S}	−0.00 ^{S}	−0.00 ^{S}	−0.00 ^{S}	−0.01 ^{S}	0.02 ^{S}	0.03 ^{S}	0.03 ^{S}
	Mean Tmin	4.33 ^{M*}	4.48 ^{M*}	4.89 ^{M*}	4.21 ^{M*}	4.21 ^{M}	4.26 ^{M*}	3.42 ^{M*}	4.18 ^{M*}	3.78 ^{M*}	5.27 ^{M*}
		0.03 ^{S}	0.02 ^{S}	0.04 ^{S}	0.03 ^{S}	0.03 ^{S}	0.02 ^{S}	0.02 ^{S}	0.03 ^{S}	0.03 ^{S}	0.05 ^{S}
	TXx	0.94 ^{M}	0.03 ^{M}	4.32 ^{M*}	−0.50 ^{M}	1.98 ^{M*}	−0.69 ^{M}	−1.24 ^{M}	0.57 ^{M}	0.38 ^{M}	1.59 ^{M}
		0.01 ^{S}	0.00 ^{S}	0.06 ^{S}	−0.01 ^{S}	0.03 ^{S}	−0.01 ^{S}	−0.01 ^{S}	0.01 ^{S}	0.00 ^{S}	0.03 ^{S}
	WSDI	4.13 ^{M*}	2.82 ^{M*}	3.65 ^{M*}	1.01 ^{M}	3.75 ^{M*}	0.47 ^{M}	0.11 ^{M}	2.63 ^{M}	3.28 ^{M}	3.14 ^{M*}
		0.6 ^{S}	0.00 ^{S}	0.35 ^{S}	0.00 ^{S}	0.44 ^{S}	0.00 ^{S}	0.00 ^{S}	0.31 ^{S}	0.36 ^{S}	0.34 ^{S}
	SU	2.48 ^{M*}	1.63 ^{M}	0.00 ^{M}	0.92 ^{M}	−1.32 ^{M}	−1.32 ^{M}	−1.98 ^{M*}	−0.24 ^{M}	2.77 ^{M*}	2.57 ^{M*}
		0.53 ^{S}	0.31 ^{S}	0.00 ^{S}	0.16 ^{S}	−0.26 ^{S}	−0.26 ^{S}	0.00 ^{S}	−0.15 ^{S}	0.53 ^{S}	0.66 ^{S}
	DTR	2.69 ^{M*}	−1.16 ^{M}	−0.38 ^{M}	−4.95 ^{M*}	−3.15 ^{M*}	−4.48 ^{M*}	−4.14 ^{M*}	−1.76 ^{M}	1.53 ^{M}	−2.73 ^{M*}
		0.01 ^{S}	−0.00 ^{S}	−0.00 ^{S}	−0.03 ^{S}	−0.02 ^{S}	−0.03 ^{S}	−0.03 ^{S}	−0.01 ^{S}	0.01 ^{S}	−0.01 ^{S}
Precipitation indices	PRCPTOT	−1.40 ^{M}	−1.04 ^{M}	−3.13 ^{M*}	−1.99 ^{M*}	−3.36 ^{M*}	1.03 ^{M}	0.75 ^{M}	−0.26 ^{M}	−0.33 ^{M}	−2.76 ^{M*}
		−4.31 ^{S}	−1.20 ^{S}	−5.77 ^{S}	−15.2 ^{S}	−24.6 ^{S}	1.02 ^{S}	2.79 ^{S}	−0.23 ^{S}	−0.47 ^{S}	−7.49 ^{S}
	R10	−1.40 ^{M}	−1.23 ^{M}	−2.35 ^{M*}	−2.32 ^{M*}	−2.95 ^{M*}	0.59 ^{M}	0.68 ^{M}	−0.02 ^{M}	−1.14 ^{M}	−3.02 ^{M*}
		0.09 ^{S}	−0.04 ^{S}	−0.23 ^{S}	−0.39 ^{S}	−0.46 ^{S}	0.00 ^{S}	0.070 ^{S}	0.00 ^{S}	−0.01 ^{S}	−0.37 ^{S}
	R20	−1.32 ^{M}	−0.28 ^{M}	−1.55 ^{M}	−2.54 ^{M}	−3.40 ^{M*}	0.88 ^{M}	0.52 ^{M}	0.13 ^{M}	1.14 ^{M}	−2.93 ^{M*}
		0.06 ^{S}	0.00 ^{S}	0.00 ^{S}	−0.31 ^{S}	−0.43 ^{S}	0.00 ^{S}	0.02 ^{S}	0.00 ^{S}	0.00 ^{S}	−0.22 ^{S}
	R25	−1.06 ^{M}	−0.43 ^{M}	−1.14 ^{M}	−2.13 ^{M*}	−4.03 ^{M*}	0.26 ^{M}	1.05 ^{M}	−0.87 ^{M}	0.92 ^{M}	−2.66 ^{M*}
		−0.03 ^{S}	0.00 ^{S}	0.00 ^{S}	−0.25 ^{S}	−0.45 ^{S}	0.00 ^{S}	0.07 ^{S}	0.00 ^{S}	0.00 ^{S}	−0.12 ^{S}
	r95p	−1.12 ^{M}	−1.61 ^{M}	−1.51 ^{M}	−1.22 ^{M}	−1.15 ^{M}	0.60 ^{M}	0.72 ^{M}	−0.24 ^{M}	−0.29 ^{M}	−1.57 ^{M}
		−1.32 ^{S}	0.00 ^{S}	−1.84 ^{S}	−5.72 ^{S}	−7.18 ^{S}	0.00 ^{S}	0.00 ^{S}	−0.15 ^{S}	−0.10 ^{S}	−3.84 ^{S}
	r99p	−0.70 ^{M}	−1.99 ^{M*}	−1.53 ^{M}	−0.20 ^{M}	−2.12 ^{M*}	−0.25 ^{M}	−0.41 ^{M}	−0.38 ^{M}	−0.09 ^{M}	−1.38 ^{M}
		0.00 ^{S}	0.00 ^{S}	0.78 ^{S}	0.00 ^{S}	−6.44 ^{S}	0.80 ^{S}	0.00 ^{S}	0.00 ^{S}	0.00 ^{S}	−1.63 ^{S}
	RX1	−2.00 ^{M*}	−1.45 ^{M}	−1.06 ^{M}	−0.26 ^{M}	−1.66 ^{M}	0.01 ^{M}	−0.01 ^{M}	−0.24 ^{M}	0.00 ^{M}	−0.31 ^{M}
		−1.05 ^{S}	−0.53 ^{S}	−0.10 ^{S}	−0.09 ^{S}	−2.21 ^{S}	0.00 ^{S}	−0.03 ^{S}	−0.04 ^{S}	0.00 ^{S}	−0.13 ^{S}
	RX5	−1.68 ^{M}	−1.20 ^{M}	−1.75 ^{M}	−0.59 ^{M}	−2.10 ^{M*}	0.40 ^{M}	0.12 ^{M}	−0.57 ^{M}	−0.61 ^{M}	−2.21 ^{M}
		−1.80 ^{S}	−0.73 ^{S}	−0.57 ^{S}	−0.90 ^{S}	−3.76 ^{S}	0.22 ^{S}	0.34 ^{S}	−0.15 ^{S}	−0.17 ^{S}	−0.88 ^{S}

Note: Red = increasing and blue = decreasing.

Table 6. Seasonal trend of extreme temperature indices in different agro-ecological zones in Pakistan. Season description: winter = Nov + Dec+ Jan, spring = Feb + March + April, summer = May + June + July, autumn = Aug + Sep + Oct.

Indices	Seasons	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone1 0
Mean Tmax	WI	2.64^{M*} 0.04^{s}	2.01^{M*} 0.01^{s}	2.07^{M*} 0.02^{s}	-1.06^{M*} -0.01^{s}	-1.06^{M*} -0.01^{s}	-0.92^{M*} -0.04^{s}	-1.09^{M*} -0.01^{s}	1.74^{M*} 0.02^{s}	2.43^{M*} 0.05^{s}	3.20^{M*} 0.06^{s}
	SP	3.01^{M*} -0.05^{s}	2.44^{M*} 0.01^{s}	3.27^{M*} 0.01^{s}	1.17^{M} 0.02^{s}	1.17^{M} 0.02^{s}	1.08^{M} 0.02^{s}	0.33^{M} 0.00^{s}	1.43^{M} 0.04^{s}	2.32^{M} 0.01^{s}	2.71^{M*} 0.06^{s}
	SU	3.90^{M*} 0.02^{s}	1.97^{M*} 0.01^{s}	4.18^{M*} 0.04^{s}	-1.17^{M} $-0.01^{s s}$	-1.71^{M} -0.01^{s}	-1.97^{M*} -0.02^{s}	-1.68^{M} -0.01^{s}	0.38^{M} 0.00^{s}	1.59^{M} 0.01^{s}	2.17^{M*} 0.01^{s}
	AU	4.35^{M*} 0.04^{s}	3.53^{M*} 0.02^{s}	3.83^{M*} 0.05^{s}	-2.43^{M*} -0.01^{s}	-2.48^{M*} -0.01^{s}	-2.36^{M*} -0.02^{s}	-2.46^{M*} -0.02^{s}	1.75^{M} 0.02^{s}	2.64^{M*} 0.02^{s}	1.61^{M} 0.01^{s}
Mean Tmin	WI	0.27^{M} 0.00^{s}	1.78^{M} 0.02^{s}	1.45^{M} 0.01^{s}	2.01^{M*} 0.02^{s}	2.08^{M*} 0.02^{s}	2.07^{M*} 0.02^{s}	0.94^{M} 0.01^{s}	1.82^{M*} 0.02^{s}	0.73^{M} 0.00^{s}	4.42^{M*} 0.07^{s}
	SP	3.30^{M*} 0.04^{s}	3.26^{M*} 0.02^{s}	2.57^{M*} 0.03^{s}	3.44^{M*} 0.05^{s}	3.44^{M*} 0.05^{s}	3.20^{M*} 0.04^{s}	2.02^{M*} 0.02^{s}	2.78^{M*} 0.05^{s}	2.80^{M*} 0.04^{s}	4.18^{M*} 0.06^{s}
	SU	4.60^{M*} 0.03^{s}	2.43^{M*} 0.01^{s}	3.08^{M*} 0.04^{s}	1.23^{M} 0.00^{s}	1.23^{M} 0.00^{s}	0.92^{M} 0.00^{s}	2.43^{M*} 0.01^{s}	3.08^{M*} 0.02^{s}	3.34^{M*} 0.23^{s}	4.07^{M*} 0.03^{s}
	AU	4.57^{M*} 0.04^{s}	4.60^{M*} 0.03^{s}	5.57^{M*} 0.07^{s}	4.62^{M*} 0.03^{s}	4.63^{M*} 0.03^{s}	3.14^{M*} 0.00^{s}	3.20^{M*} 0.03^{s}	4.64^{M*} 0.05^{s}	3.54^{M*} 0.03^{s}	5.63^{M*} 0.06^{s}
TXx	WI	3.27^{M*} 0.05^{s}	1.66^{M} 0.01^{s}	1.47^{M} 0.02^{s}	0.19^{M} 0.00^{s}	2.63^{M*} 0.03^{s}	0.03^{M} 0.00^{s}	-0.75^{M} -0.00^{s}	2.58^{M*} 0.04^{s}	0.82^{M} 0.02^{s}	2.64^{M*} 0.04^{s}
	SP	2.80^{M*} 0.05^{s}	1.54^{M} 0.02^{s}	3.25^{M*} 0.06^{s}	2.59^{M*} 0.05^{s}	3.18^{M*} 0.09^{s}	2.02^{M*} 0.03^{s}	1.36^{M} 0.02^{s}	2.48^{M*} 0.07^{s}	1.52^{M} 0.05^{s}	3.48^{M*} 0.07^{s}
	SU	1.89^{M*} 0.01^{s}	1.20^{M} 0.01^{s}	4.27^{M*} 0.05^{s}	-2.23^{M*} -0.02^{s}	1.66^{M} 0.01^{s}	-2.20^{M*} -0.02^{s}	-2.94^{M*} -0.03^{s}	0.29^{M} 0.00^{s}	1.64^{M} 0.03^{s}	1.98^{M*} 0.01^{s}
	AU	3.29^{M*} 0.03^{s}	2.73^{M*} 0.03^{s}	3.97^{M*} 0.06^{s}	-2.94^{M*} -0.02^{s}	3.04^{M*} 0.02^{s}	-1.13^{M} -0.01^{s}	-1.20^{M} -0.01^{s}	1.20^{M} 0.01^{s}	2.17^{M*} 0.04^{s}	0.33^{M} 0.00^{s}
DTR	WI	3.89^{M*} 0.04^{s}	-0.31^{M} -0.00^{s}	-0.18^{M} 0.00^{s}	-3.22^{M*} -0.04^{s}	-2.43^{M*} -0.02^{s}	-3.32^{M*} -0.04^{s}	-2.87^{M*} -0.02^{s}	0.29^{M} 0.00^{s}	3.02^{M*} 0.04^{s}	-1.38^{M} -0.01^{s}
	SP	1.85^{M} 0.02^{s}	0.88^{M} -0.00^{s}	1.86^{M} 0.01^{s}	-1.86^{M} -0.02^{s}	-0.36^{M} 0.00^{s}	-1.72^{M} -0.01^{s}	-1.52^{M} 0.12^{s}	-0.60^{M} 0.00^{s}	1.32^{M} 0.01^{s}	-0.33^{M} 0.00^{s}
	SU	-1.20^{M} 0.00^{s}	-1.29^{M} 0.00^{s}	-0.38^{M} 0.00^{s}	-3.42^{M*} -0.02^{s}	-1.97^{M*} -0.01^{s}	-3.46^{M*} -0.02^{s}	-2.94^{M*} -0.02^{s}	-2.34^{M*} -0.02^{s}	-0.95^{M} 0.00^{s}	-1.38^{M} -0.00^{s}
	AU	1.44^{M} 0.01^{s}	-2.19^{M*} -0.01^{s}	-2.65^{M*} 0.02^{s}	-4.83^{M*} -0.05^{s}	-4.16^{M*} -0.04^{s}	-4.25^{M*} -0.04^{s}	-4.52^{M*} -0.04^{s}	-2.06^{M*} -0.02^{s}	-0.50^{M} 0.00^{s}	-3.57^{M*} -0.03^{s}

Note: * shows significance at $p = 0.05$. ^{M} means Mann–Kendall trend, and ^{S} means Sen slope. Red = increasing and blue = decreasing.

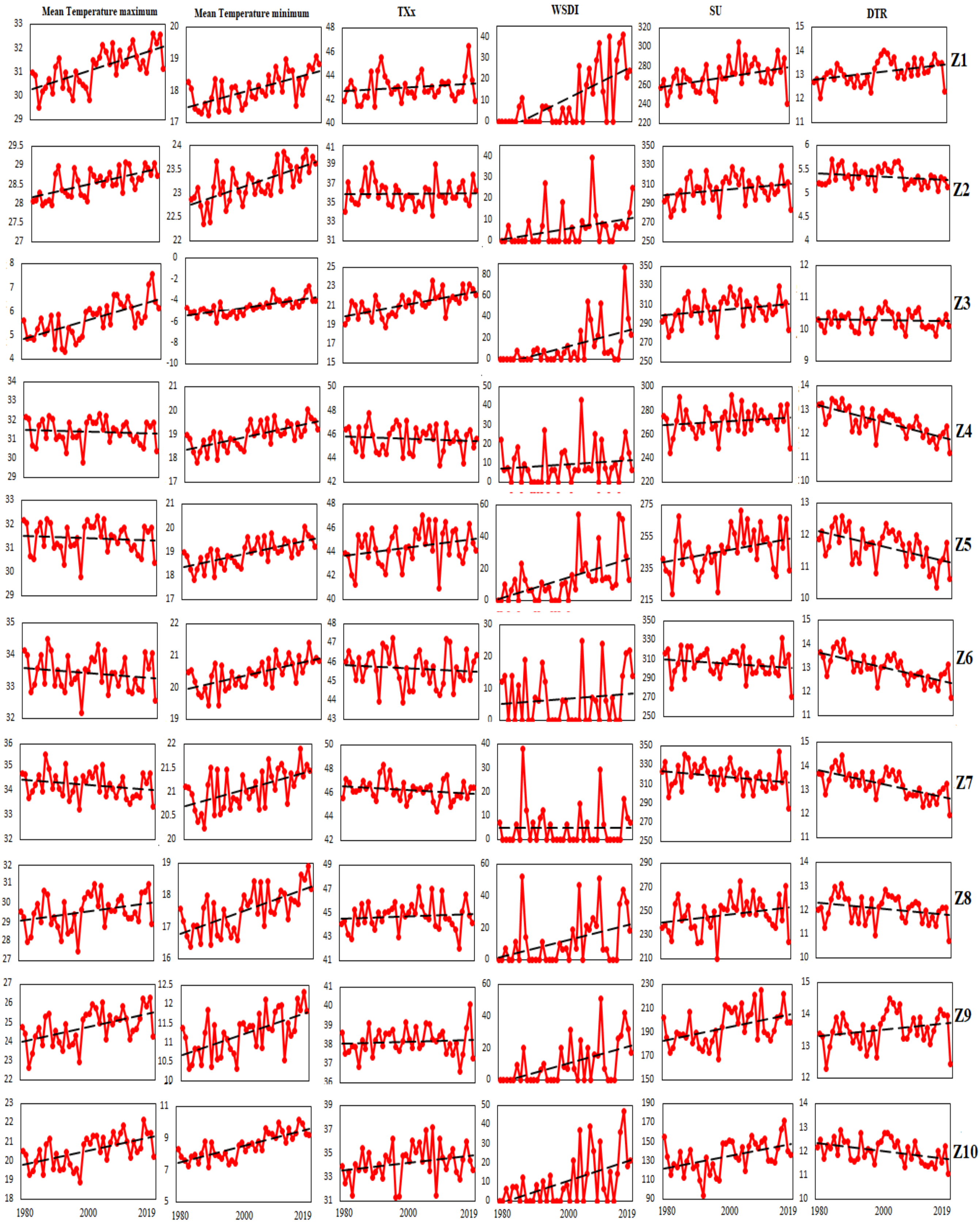

Figure 5. Temperature extreme indices temporal trend over AEZs of Pakistan (1980–2019).

The spring and summer seasons were badly affected by the warming trend of hot extremes in different AEZs. During the winter, mean Tmax (Tmin) and TXx showed an increasing trend in 5 (10) and 10 AEZs, respectively, and DTR showed a decreasing trend in 6 AEZs because of increasing mean Tmin. For spring, mean Tmax (Tmin) and TXx showed an increasing trend in 9 (10) and 10 AEZs, respectively, and DTR showed a decreasing trend in 5 AEZs. In Pakistan, mean Tmax (Tmin) and TXx showed an increasing trend in 9 (10) and 7 AEZs, respectively, and DTR showed a decreasing trend for 10 AEZs during summer seasons. Autumn seasonal results showed a similar increasing trend in mean Tmax (Tmin) and TXx with 9 (10) and 7 AEZs, respectively, and DTR showed a decreasing trend in 7 AEZs. DTR decreased because of the rise in the mean Tmin in different zones of Pakistan, as seen in Table 6.

3.4. Long-Term Trend in Precipitation Indices

During 1980–2019, the trend of intensity and frequency of precipitation in all AEZs throughout Pakistan decreased as shown in Table 5. On an annual scale, PRCPTOT decreased in most AEZs with a range of −0.26–−3.36 but increased in zones[6,7] with a range of 0.75–1.03. A significant decreasing trend of PRCPTOT was found in zones[3,4,5,10]. Over the study period, the number of heavy precipitation days (R10mm, R20mm, and R25mm) showed a decreasing trend in the majority of the AEZs. The trend of moderate precipitation days (R10mm) was decreasing in 80% of AEZs (with the exception of zones[6,7]) with magnitudes ranging from −0.02 to −3.02, and the trend of heavy precipitation days (R20mm) was decreasing in 60% of AEZs with magnitudes ranging from −0.28 to −3.40. The number of extremely heavy precipitation days (R25mm) calculated the decrease in 70% AEZs with high magnitude and an increasing trend in zone[6,7,9] with a range of (0.26)–(1.05). The number of wet days is determined by calculating r95p and r99p. The number of very wet days (r95p) showed a declining trend in 80% of AEZs (with the exception of zones[6,7]), while the number of extreme wet days (r99p) showed a declining trend with a range of −0.09–−2.12 in all AEZs during 1980–2019. The maximum 1- and 5-day precipitation (RX1, RX5) showed the annual 1-day and consecutive 5-day precipitation. There was a decline in RX1 and RX5 in the majority of AEZs of Pakistan, with values ranging from −0.04 to −2.00 and −0.57 to −2.21, respectively. No trend was observed in zone[9] for RX1, and an increasing trend was calculated in zone[6] and zones[6,7] for RX1 and RX5, respectively. Figure 6 shows that the overall annual precipitation indices trend was declining in most of the AEZs, but a few AEZs showed an increasing trend with minute magnitude as represented in Table 5. According to the seasonal analysis of precipitation in Table 7, a fluctuating trend was observed in different seasons. RX1 and RX5 showed a significant reduction for all of the AEZs. During the spring and summer seasons, 80% of AEZs had a decreasing trend of RX1 with values ranging from −0.24 to 2.68, but during winter and autumn, 60% of AEZs had a decreasing trend of RX1 with values ranging from −0.15 to −1.85. Similarly, for RX5, summer showed a decreasing trend in all AEZs except for zone[6] with magnitudes in the range −0.17–1.59. During the winter and spring, RX5 declined in 70% and 80% of AEZs in Pakistan, respectively, but in autumn, RX5 showed an increasing trend in all AEZs except zone[3,8,10]. In most AEZs, a visible negative shift in RX5 occurred during the winter, spring, and summer seasons. RX1 declined during spring and summer. Details of significant trends are shown in Table 7.

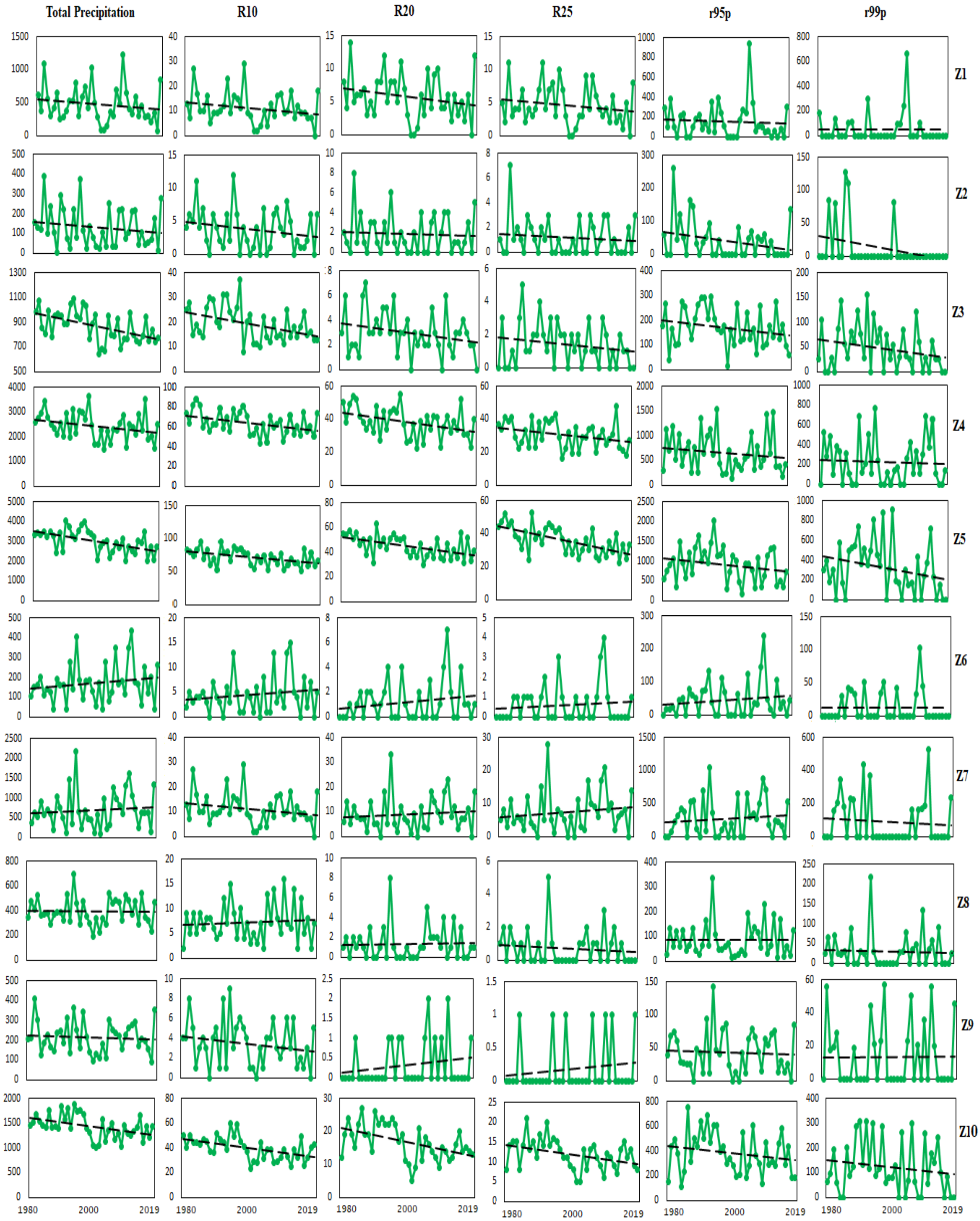

Figure 6. Precipitation extreme indices temporal trend over agro-ecological zones of Pakistan (1980–2019).

Table 7. Seasonal trend of extreme precipitation indices in different agro-ecological zones in Pakistan. Season description: Winter = Nov + Dec + Jan, spring = Feb + March + April, summer = May + June + July, autumn = Aug + Sep + Oct.

Indices	Seasons	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10
RX1	WI	-1.24^{M}	-1.98^{M*}	-0.17^{M}	0.68^{M}	0.68^{M}	-0.82^{M}	0.50^{M}	1.10^{M}	-0.45^{M}	-0.26^{M}
		-0.90^{S}	-0.23^{S}	-0.02^{S}	0.41^{S}	0.41^{S}	-0.04^{S}	0.17^{S}	0.17^{S}	-0.04^{S}	-0.15^{S}
	SP	-1.50^{M}	-0.87^{M}	-1.71^{M}	-1.38^{M}	-1.38^{M}	0.26^{M}	0.50^{M}	-0.38^{M}	-0.73^{M}	-2.68^{M*}
		-0.62^{S}	-0.01^{S}	-0.36^{S}	-1.06^{S}	-1.06^{S}	0.01^{S}	0.09^{S}	-0.70^{S}	-0.09^{S}	-0.33^{S}
	SU	-0.36^{M}	-0.24^{M}	-0.31^{M}	-1.29^{M}	-1.29^{M}	0.05^{M}	0.17^{M}	-0.47^{M}	-1.06^{M}	-0.87^{M}
		-0.07^{S}	-0.08^{S}	-0.05^{S}	-1.50^{S}	-1.50^{S}	0.02^{S}	0.18^{S}	-0.09^{S}	-0.04^{S}	-0.15^{S}
	AU	0.38^{M}	-0.08^{M}	-1.08^{M}	-0.15^{M}	-0.51^{M}	0.00^{M}	0.36^{M}	-0.33^{M}	-0.40^{M}	-1.85^{M}
		0.00^{S}	-0.00^{S}	-0.17^{S}	-0.08^{S}	-0.08^{S}	0.00^{S}	0.09^{S}	-0.05^{S}	-0.02^{S}	-0.22^{S}
RX5	WI	-0.87^{M}	-1.64^{M}	0.12^{M}	-0.87^{M}	-0.22^{M}	-0.52^{M}	0.22^{M}	0.89^{M}	-0.87^{M}	-0.82^{M}
		-1.37^{S}	-0.29^{S}	0.02^{S}	-0.45^{S}	-0.29^{S}	-0.06^{S}	0.11^{S}	0.20^{S}	-0.25^{S}	-0.83^{S}
	SP	-1.40^{M}	-1.50^{M}	-1.94^{M*}	-1.61^{M}	-1.64^{M}	0.29^{M}	0.50^{M}	-0.36^{M}	-0.89^{M}	-2.41^{M*}
		-0.92^{S}	-0.10^{S}	-1.07^{S}	-2.27^{S}	2.27^{S}	0.03^{S}	0.13^{S}	-0.15^{S}	-0.29^{S}	-2.16^{S}
	SU	-0.29^{M}	-0.38^{M}	-0.38^{M}	-1.20^{M}	-1.20^{M}	0.17^{M}	-0.17^{M}	-0.80^{M}	-0.45^{M}	-1.59^{M}
		-0.13^{S}	-0.34^{S}	-0.21^{S}	-3.18^{S}	-3.18^{S}	0.12^{S}	-0.19^{S}	-0.41^{S}	-0.15^{S}	-1.31^{S}
	AU	0.47^{M}	0.54^{M}	-0.92^{M}	0.17^{M}	0.17^{M}	0.87^{M}	1.15^{M}	-0.19^{M}	0.17^{M}	-1.31^{M}
		0.12^{S}	0.04^{S}	-0.33^{S}	0.47^{S}	0.47^{S}	0.18^{S}	0.29^{S}	-0.04^{S}	0.02^{S}	-0.84^{S}

Note: * shows significance at $p = 0.05$. ^{M} means Mann–Kendall trend, and ^{S} means Sen slope. Red = increasing and blue = decreasing.

3.5. Principal Component Analysis

PCA is a procedure of transformation of possibly correlated variables into small uncorrelated variables called factors that increase variance. The PCA factors were selected by using an eigenvalue threshold > 1, and two factors were chosen in the current study analysis with a total variance of 76% in the case of temperature and 91% in the case of precipitation. Table 8 shows the characteristics of temperature and precipitation variability in Pakistan. In the case of variance in temperature, factor 1 (F1) explains 50% of the total variance in extreme temperature, where all indices show the warming trend. According to F1, mean Tmin (Tmax) explains 0.97 (0.86) of temperature variance, WSDI (SU) shows 0.74 (0.76) in the region. DTR shows a weak contribution to temperature variance with a factor value of (0.13) across Pakistan. Factor 2 (F2) shows 26% of the total variance. DTR explains the maximum variance in temperature, and Tmin (−0.20), TXx (0.19), and WSDI (0.08) have the lowest factor score in F2.

Table 8. Factor loadings of extreme temperature and precipitation variance.

Indices	Factors	
	1	2
Mean Tmax	**0.86**	0.49
Mean Tmin	**0.97**	−0.20
TXx	0.41	0.19
WSDI	**0.74**	0.08
SU	**0.76**	0.53
DTR	0.13	**0.99**
Variance (%)	0.50	0.26
PRCPTOT	**0.89**	0.42
R10	**0.95**	0.20
R20	**0.96**	0.23
Rnn	**0.94**	0.27
R95p	0.61	**0.66**
R99p	0.29	**0.86**
RX1	0.18	**0.92**
RX5	0.26	**0.93**
Variance (%)	0.51	0.40

Note: The bolded text shows the highest factor's score.

Mean Tmin, mean Tmax, WSDI, and SU increased, increasing temperature extremes. For the precipitation indices, factor scores, namely F1 and F2, were computed that explain 51% and 40% of the total variance of precipitation from 1980 to 2019. According to F1, PRCPTOT (0.89), R10 (0.95), R20 (0.96), and Rnn (0.94) have dominant scores and effectively contributed to the precipitation extreme changes in Pakistan. The index RX1 has the lowest factor score (0.18). The index of RX5 dominates score (0.93) and R10 has the lowest score (0.20) in F2, which accounts for 40% of the total variance in precipitation extreme in the region. The indices R10 (0.20), R20 (0.23), and Rnn (0.27) had the lowest relative scores in F2.

3.6. Influence of Temperature Extremes on Drought

The annual and seasonal relationship between temperature extremes and drought in different AEZs of Pakistan were investigated by a standardized approach of Pearson's correlation (Figures 7 and 8). For this study, the different ground station data in the same zone were averaged. Annual and seasonal data were used to show the relationship between climate extremes and drought. The analysis revealed a strong correlation between temperature extremes and drought on an annual and seasonal timescale across Pakistan. All temperature indices (mean Tmin, mean Tmax, TXx, WSDI, SU, DTR) were closely correlated with drought events on an annual scale. Temperature events and drought events had a negative correlation, which suggests that higher temperatures cause negative values of drought (dry conditions) and therefore greater drought strength. In zones[1,4,5,8,9], temperatures severely affected drought occurrence as compared to zones[2,3,6], as shown in Figure 7.

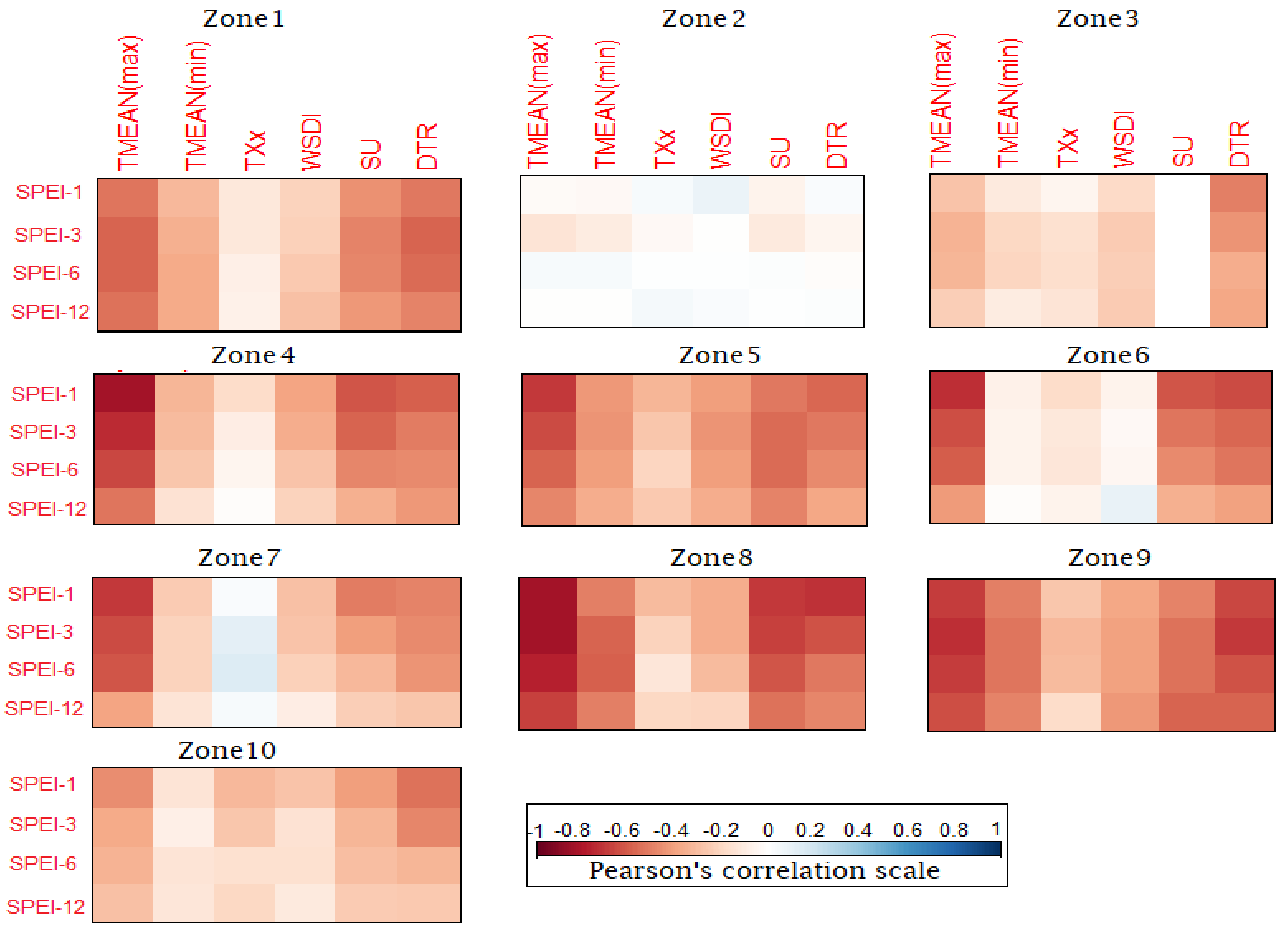

Figure 7. Pearson's correlation between annual temperature extreme indices and SPEI.

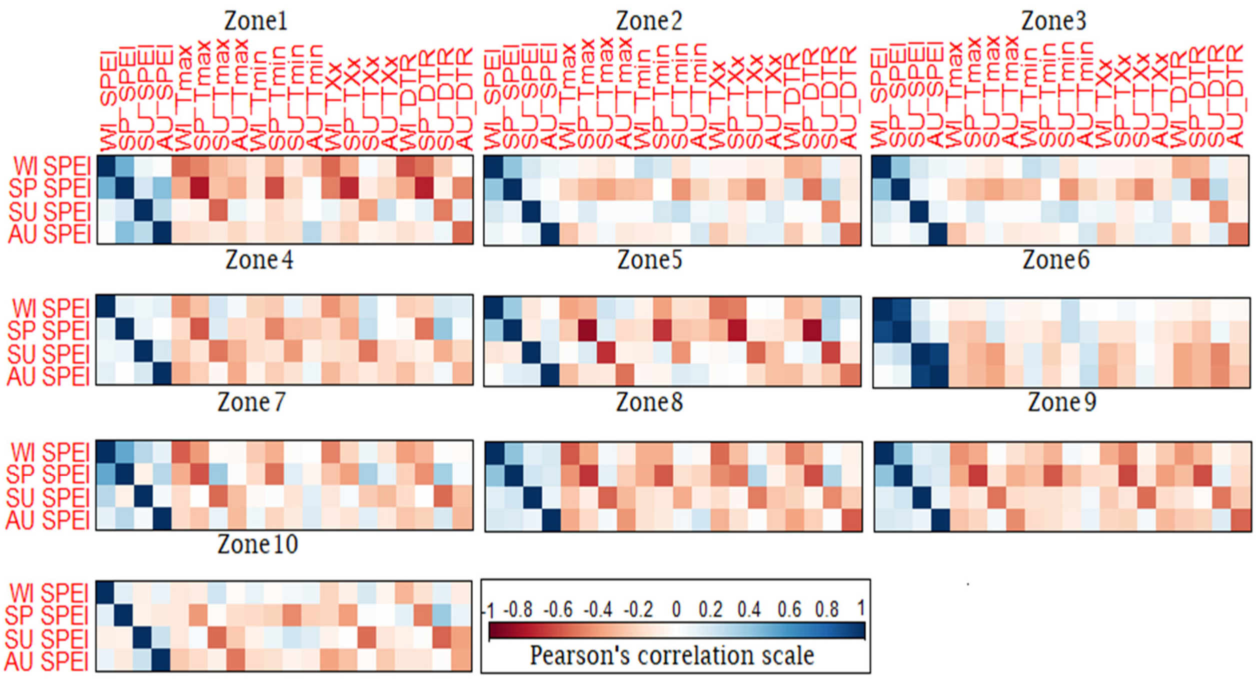

Figure 8. Pearson's correlation between seasonal temperature extreme indices and SPEI-3.

Particularly, zone[2] was less affected by the temperature extremes from 1980 to 2019. Most zones were affected severely by mean Tmax, mean Tmin, SU, and DTR. On the seasonal time scale, the correlation between seasonal temperature extremes and seasonal SPEI was fluctuating. During the spring and summer, temperature influenced the drought pattern and increased it in most AEZs. Moreover, winter temperature delineated drought occurrence except in zones[2,6,3], as represented in Figure 4. These correlations between drought events and climate extremes in different AEZs of Pakistan are well captured by the scatterplots.

3.7. Influence of Precipitation Indices on Drought

To investigate the impact of precipitation on drought variability, Pearson's correlation was used. The analysis concluded that on an annual scale, precipitation indices showed a strong positive correlation with drought events in all zones except zones[2,9]. Results depicted in Figure 9 show that higher precipitation levels minimize drought conditions; by increasing precipitation, drought can be controlled in all zones. Zones[1,3,4,5,7,8,10] showed a strong positive correlation with the drought pattern. Precipitation indices (including PRCPTOT, r95p) were strongly linked with drought variability. However, precipitation indices did not have a strong correlation with drought in zone[2], which means that drought events did not rely on the precipitation condition there. The precipitation indices r99p and R10/R20 did not support drought conditions in zones[5,6] and zone[9], respectively. On the seasonal scale, precipitation indices showed a good correlation with drought events in all zones except zones[2,10]. Overall, seasonal precipitation showed a fluctuating relationship with drought occurrence in all zones. Zones[2,5,6] had a weak correlation of seasonal precipitation and drought, as shown in Figure 10.

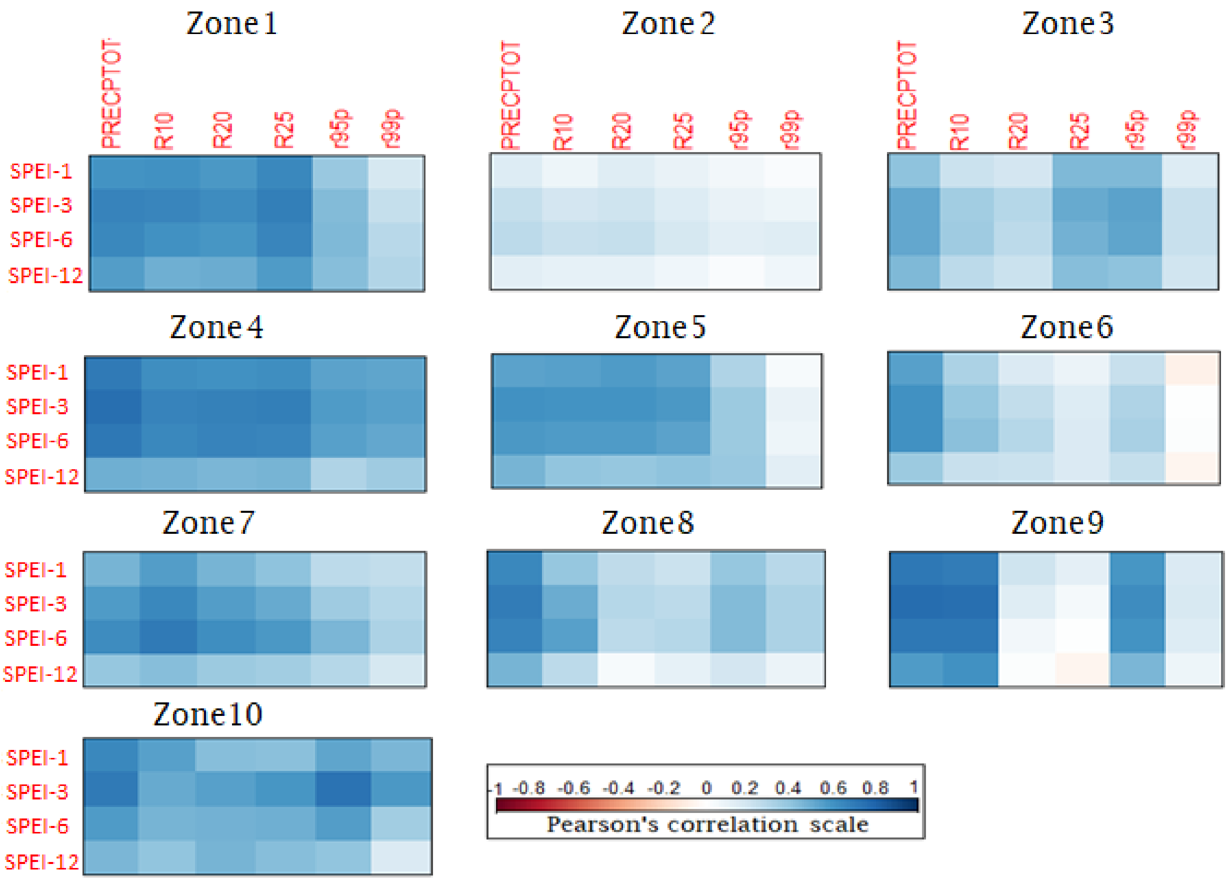

Figure 9. Pearson's correlation between annual precipitation extreme indices and SPEI.

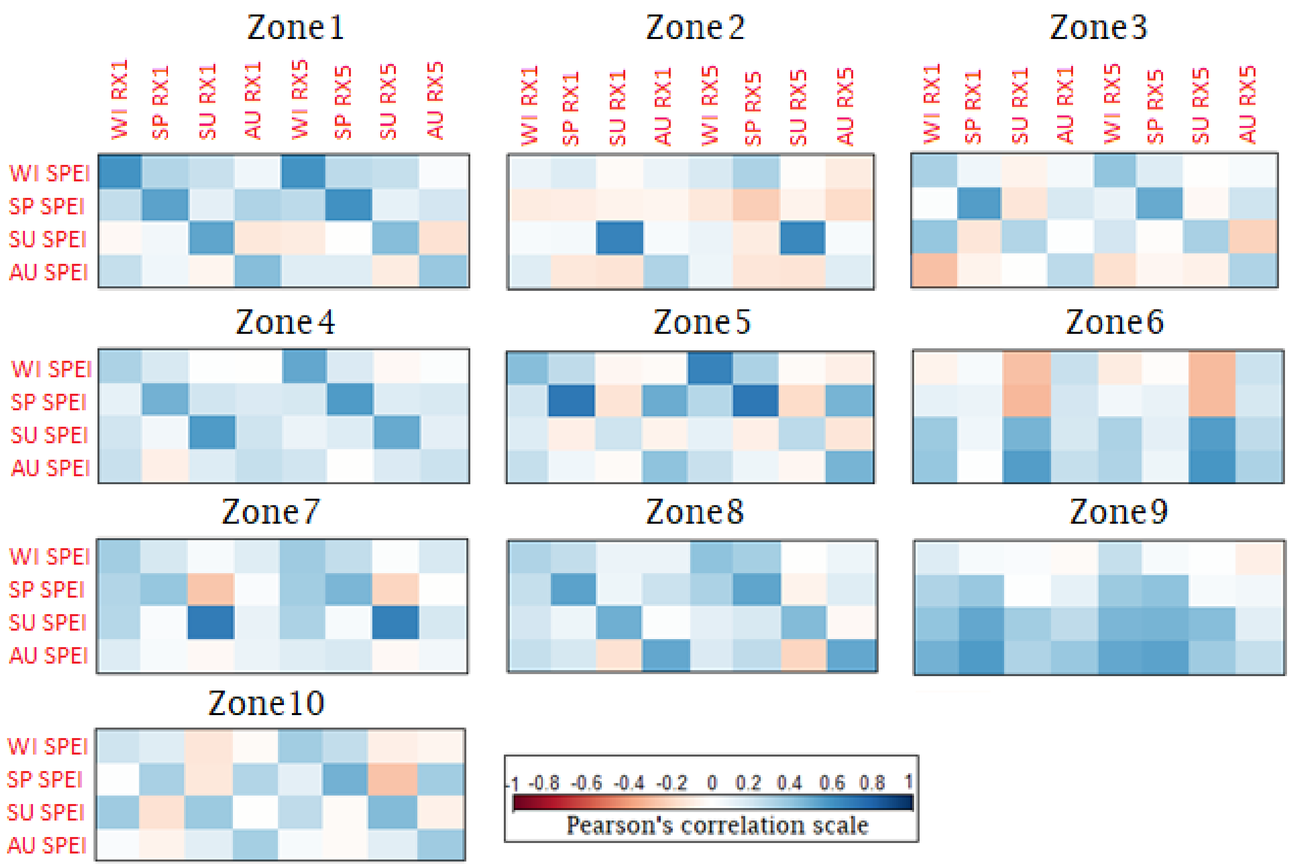

Figure 10. Pearson's correlation between seasonal precipitation extreme indices and SPEI.

4. Discussion

The average annual and seasonal spatial trends of climate extremes (temperature and precipitation) over the AEZs in Pakistan from 1980 to 2019 were calculated, revealing an increasing trend of temperature extremes and a decreasing trend of precipitation. The mean Tmax increased in zones^{1,2,3,8,9,10}, while Tmin increased in all AEZs. The results of the present study supported the previous findings of H. Sajjid (2018), who concluded that there is a growing trend in the mean Tmax in Sindh province and a similar rising trend computed for Baluchistan province in Pakistan [70].

Over the study period, the central part of Pakistan experienced a decreasing trend of mean Tmax, and an increase in mean Tmin was observed in Punjab province. Ahmed et al. (2016) observed that Punjab province had a rising trend for mean Tmin but a decrease noted in mean Tmax [71]. A study on the trend of temperature extremes in Pakistan was conducted by Khan, and it revealed that the annual temperature is rising faster in the southern part of Pakistan, and the mean Tmin is increasing faster than the mean Tmax. This study also concluded that the faster increase in the mean Tmin caused the decline in DTR [72,73]. Since 1980, the precipitation extremes in all AEZs have had a reverse pattern of trend. A decreasing trend was found in eight AEZs for the PRCPTOT, R10p, r95p, RX1, and RX5 indices, in seven AEZs for R20, and in all AEZs for r99p in the region shown in Table 5. A negative trend of SPEI (dryness) was also computed in seven AEZs, with zones1,9 facing the worst drought situation. In regard to the the spatial and temporal variability of drought in Baluchistan, a negative (decreasing) trend of precipitation was found in 70% of stations in Baluchistan over the past 36 years [34]. The southern part of Pakistan, including the Sindh and Baluchistan provinces, have experienced a decreasing trend in SPEI over time, indicating drying conditions, while the central part has had a wetting trend with an increase in SPEI [68,74]. The current study's findings are clearly in line with a previous study that analyzed drought events in Baluchistan and found, using

MK, that SPI mostly decreased, suggesting that drought vulnerability increased in the province [75]. The precipitation extremes trend showed significant and nonsignificant changes, while the temperature extremes trend revealed significant changes across the region [76].

Assessment of long-term drought characteristics of drought including drought duration, drought frequency, and drought intensity in different AEZs of Pakistan shows that SPEI-1 had a maximum drought duration of 5 months and that SPEI-12 had a minimum drought duration of 4.1 months. The drought duration decreased with the SPEI time scale in the study region. Our finding is supported by a study of historical analysis of drought magnitude and severity in Pakistan resulted that the 3-month timescale showed a higher number of drought years while the 12-month timescale showed a lower number [77]. The opposite results were found for drought frequency. SPEI timescale tends to increase the drought frequency, which means that SPEI-12 had higher and SPEI-1 had lower drought frequency. The mean drought frequency was 14.8%, 15.1%, 16.5%, and 17.2% for SPEI-1, SPEI-3, SPEI-6, and SPEI-12, respectively, over the Pakistan region. The finding of the present work is consistent with observations that drought frequency at large SPEI scales (SPEI-6, -12) persist more than those at short SPEI scales (SPEI-1, -3) [67]. These short- and long-term droughts have distinct effects on the physical environment; for example, short-term droughts pose major risks to agriculture, while longer-term droughts events affect the hydrological cycle [78,79]. Drought intensity tended to increase with the SPEI timescale. The mean drought intensity over Pakistan was 0.01, 0.03, 0.06, and 0.08 for the timescales SPEI-1, SPEI-3, SPEI-6, and SPEI-12, respectively. During 1981–2018, SPEI effectively exacerbated severe drought events at higher SPEI timescales while mild at lower timescales in the Baluchistan province [80]. The southern part of the region is suffering from high-intensity drought.

On the seasonal scale, according to SPEI trend analysis, the winter, spring and summer seasons experienced alarming drought events, and precipitation findings showed a major decline in precipitation (RX1, RX5) over the Pakistan region, as shown in Table 7. The north part of Baluchistan faces severe drought during the summer. The northwest of Baluchistan is experiencing mild to severe drought during the winter season, while the north part is affected by extreme drought during the summer [69,71]. During the summer, a visible decreasing trend in precipitation was observed across the country [81]. The key drivers of the climate variability in the region are the El Niño Southern Oscillation and variations in sea surface temperature (SST) in the Indian and Pacific oceans. Temperature variability over small regions is likely to be influenced by land–ocean linking mechanisms and complex mid atmosphere processes [82,83]. Iqbal and Athar (2018) concluded that monthly IOD has strongly impacted the precipitation cycle in Baluchistan, Pakistan. Moreover, they concluded that AMO had a moderate correlation and ENSO had a strong correlation with precipitation on annual basis [41].

According to PCA (Table 8), the factor scores showed that the variance in precipitation was greater than the variance in total temperature in the region. Drought events were more sensitive to precipitation changes in the different AEZs of Pakistan. Less precipitation causes drought occurrence, while high precipitation leads to wet conditions. According to Pearson's correlation, a strong positive relationship between precipitation and drought occurrence means that high precipitation comes with wetting conditions (no drought). In Figures 9 and 10, most of the zones showed a good correlation between SPEI and precipitation indices annually and seasonally. On the seasonal scale, seasonal precipitation indices showed a good correlation with drought events in all zones except in zones^{2,10}. In the case of temperature indices, Pearson's correlation described a strong negative correlation between SPEI and temperature indices as shown in Figures 7 and 8. The negative correlation means that a higher temperature in the study area comes with negative drought value (dry conditions). Moreover, temperature and drought events showed a negative correlation, which means that higher temperatures lead to negative values of drought, i.e., higher drought strength. In zones^{1,4,5,8,9}, the temperature severely affected drought occurrence as compared to zones^{2,3,6}, as shown in Figure 7. Ref. [84] showed that drought events had a positive correlation with the precipitation over Sindh, Pakistan during 1951–2010. Another study in Pakistan analyzed precipitation's relationship with drought and concluded that drought severity is decreased by high precipitation [37]. During the spring and summer, temperature affected the drought SPEI pattern and increased it in a majority of AEZs. The rise in temperature in most of the parts of Pakistan has increased drought frequency [37].

5. Conclusions

SPEI, temperature, and precipitation indices were used to investigate long-term shifts in drought and climate extremes over AEZs in Pakistan from 1980 to 2019. These were characterized by increasing or decreasing trends over the past 40 years. This research examined the effect of climate extreme variability in drought changes (i.e., annual and seasonal trends) in the AEZs. The drought characteristics (frequency, duration, and intensity) were investigated at SPEI timescale (SPEI-1, SPEI-3, SPEI-6, and SPEI-12). Overall, rising trends of SPEI and temperature extremes over the last 40 years were discovered, with distinct temporal patterns over different AEZs. Our study indicates a decreasing trend of precipitation in most of the AEZs of Pakistan. The most widespread and significant changes were observed in the zones^{1,2,8,9} located in the southern and southwestern regions of Pakistan. Precipitation was more sensitive than temperature to cause drought conditions in the present study area. According to the MK trend test and Sen's slope, the annual drought and temperature trends were increasing, while precipitation trends were decreasing in the region. Seasonally, drought was more persistent during the winter, spring, and summer; zones^{1,5,9} were more vulnerable to seasonal droughts. Temperature extremes increased significantly across the AEZs of Pakistan during winter, spring, summer, and autumn, but a weaker rising trend was observed in summer as compared to the other seasons. According to trend analysis and Sen's slope, it was concluded that visible changes occurred in precipitation extremes, particularly during the winter, spring, and summer seasons. A decreasing trend of precipitation was observed, especially in winter, spring, and summer, resulting in severe drought within the same seasons. The high warming trend in the region took part to decrease the precipitation and put extra pressure on water demands for agricultural activities in these AEZs. The prolonged drought in the region triggered warmer and drier weather conditions. During the spring seasons, the La Niña and El Niño events in the region often cause frequent warm and cold extremes [85]. The relationship of long-term temperature and precipitation extremes trends (which are significant and substantial) with the interannual variability associated with SPEI drought is important for Pakistan. The present study's conclusions have deep implications for the largest risks for societal and economic development in the winter and spring, as well as for creating climate mitigation and adaptation strategies. For adequate plans to mitigate the impact of climate extremes (temperature and precipitation) on society, the observed warming and drying conditions in Pakistan require future efforts to analyze drought driving factors to develop and to improve drought prediction skills by taking into account climate scenarios.

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