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Investigations into precipitation and drought climatologies in South Central Asia with special focus to Pakistan over the period of 1951-2010

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Abstract

The climatology of precipitation and drought are analyzed by using different indices in the South Central Asian (SCA) region. The spatial precipitation pattern is delineated by using the Principal Component Analysis (PCA) over the period of 1951-2010, which identifies six sub regions in the SCA. The monthly and annual trends of precipitation was analyzed by applying the five statistical tests, namely; t-Student's, Mann-Kendal, Spearman's Rho for linear trend while turning point and Sen's Slope for randomness and slope magnitude respectively at $\alpha = 0.05$ significance level. The timeseries analysis show data similiarity between Global Precipitation Climatology Centre (GPCC) and area weighted precipitation of 52 meteoroloigcal stations in Pakistan, which results in a high correlation ($R^2 = 0.93$). The two main drought periods were identified (1971 and 2000-2002) and 2001 was the extremely dry year in SCA region. The drought in 1952 was the most severe in Pakistan, while the longest drought period was 2000-2002. The intense droughts were reported in the whole SCA region when the annual percent of precipitation was below 80%. It is noted that A-5 region (north east SCA) is the most vulnerable where 19 droughts were reported. The monthly precipitation analysis shows a significant increasing trend in the months of September and June in A-3(northwest SCA) and A-5 region, respectively, while a decreasing trend is observed in January and August in A-4 region (east SCA). The decadal analysis shows significant decreasing trend (-21.5mm/decade) in region A-4, while the highest increasing trend (17.1 mm/decade,7.5 mm/decade) is observed in Paksitan and A-5 region respectively.

Keywords: PCA, Trend Analysis, Precipitation, Drought, Statistical Tests, SCA

1. Introduction

The most important climatological factor responsible for drought or flood is precipitation. The precipitation variability can cause both types of natural hazards. As demonstrated by Gocic and Trajkovic (2013a), the analysis of precipitation and drought climatologies provides very useful information for improving the strategies of water management, environmental protection, agricultural production and socioeconomic development for a certain region.

Drought is both; a disaster and a hazard that occurs naturally due to the deficiency of precipitation over a region. Moreover, the frequency, severity and duration of drought varies across different climatic zones (Wilhite, 1993; Paulo et al., 2012). It is also considered the worst climatic extremes affecting more people than any other form of natural disasters (Wilhite, 2000). It can be classified into four classes; meteorological, agricultural, hydrological and socio-economic drought (Dracup et al., 1980; Wilhite and Glantz, 1985).

In the past, several studies have been conducted and different drought indices were developed (e.g., Shahid, 2008; Mishra and Singh, 2010; Pietzsch and Bissolli, 2011; Tabari et al., 2012). Hisdal et al. (2001) suggested that the precipitation variability explains the trends of drought occurrence, frequency and duration. Although precipitation trends have been compared and analyzed by the numerous scientists (e.g., Gemmer et al., 2004; Liu et al., 2008; Tabari et al., 2012; Hanif et al., 2013) but very few studies measured the global precipitation with accuracy as it is the most challenging task of this modern era.

Most of the research reports published by the Intergovernmental Panel on Climate Change (IPCC) indicated that the global mean surface temperature as the most common indicator for climate change. It is noted that more evaporation takes place as the temperature increases and this causes more precipitation as well (Karl et al., 1997). A study conducted on 14 powerful models shows an increasing precipitation at high latitudes while decreasing at subtropical latitudes by considering the anthropogenic impact on global precipitation and latitudinal redistribution of mean precipitation (Zhang et al., 2007).

According to RupaKumar et al. (1992), the long term rainfall data indicates an increasing trend in monsoon seasonal rainfall in the northwest India. Similarly, a decreasing trend in the monsoon seasonal rainfall and increasing trend in temperatures was observed by using the long term dataset of whole India as demonstrated by Kothyari and Singh (1996). Similarly, significant increasing and decreasing trends have observed over the several stations in China during the last 50 years (Gemmer et al., 2004). Treydte et al. (2006) determined an increasing precipitation trend caused by the global climate change during the 20^{th} century. Multi model ensemble techniques showed an increase of 20-24% in precipitation projected over Arabian Peninsula and some areas of Pakistan, Nepal and northwest India (Kirpalani et al., 2007). According to Ramesh and Goswami (2007), the linear and spatial precipitation trends in daily gridded observed data (1951-2003) shows that Indian summer monsoon is shrinking both; temporally and spatially. However, in Pakistan, the percentage of effective rainfall decreases as the distance from the sea increases except for northern area (Adnan and Khan, 2009). Kumar et al. (2010) detected a significant annual increase in rainfall over northern India. Recently, Hanif et al. (2013) used 60 years data and observed a significant increase in seasonal and annual rainfall in the upper parts of Pakistan, but no significant change is noted in seasonal and annual rainfall in southern parts of that country. Moreover, monsoon rainfall has shifted a bit westward.

From these brief reviews, it is apparent that there is a changing trend in seasonal extreme rainfall observed in different parts of Asia during the recent decades, but the impacts of this variable in the region has not identified yet. In this study, a detailed precipitation analyses carried out and its trends were studied over the period of 1951-2010 in SCA region by using the observational and GPCC gridded data of horizontal resolution (0.5°×0.5°). Furthermore, these investigations helps indicating areas which are highly vulnerable to floods and droughts in the selected region.

The objectives of these investigations are: (1) to segregate the precipitation by using Principal Component Analysis (PCA) in SCA region, which would help to determine the weather influencing system, (2) to find the rainfall variability on monthly basis along annual trends analysis by using five statistical tests such as t-Student's, linear regression, Mann-Kendal, Spearman's Rho, while turning point and Sen's Slope for randomness and slope magnitude respectively at $\alpha = 0.05$ significance level (3) to delineate the correlation among different precipitation and drought indices. Finally, to investigate the drought climatologies and vulnerable areas in the SCA region with special focus on Pakistan for the period of 1951-2010, which may be helpful for water management and agricultural planning for sustainable development.

2. Data and methodology

The study area lies in the domain of (20.25°N to 45.75°N and 59.25°E to 80.75°E) and comprises Afghanistan, China, India, Iran, Krygyzstan, Pakistan, Tajikistan, Turkmenistan and Uzbekistan called South Central Asian (SCA) region (Fig.1). The climate of this region is arid, semi arid and temperate according to Koppen classification (Koppen, 1999). The maximum amount of rainfall is observed in the western and eastern parts (eastern Pakistan and India) in the SCA region due to western disturbances (WDs) and monsoon rainfall respectively (Yadav et al., 2012). Sixty years (1951-2010) of monthly precipitation data ($0.5^{\circ}\times0.5^{\circ}$) from the Global

Precipitation Climatological Centre (GPCC), University of Delware (UDEL, USA), Climate Research Unit (CRU, University of East Anglia (UEA), UK), precipitation over Land by NOAA (PRECIP_L) and mean ensemble is used to determine the correlation between them. The main purpose of these comparison are to determine the similarity and suitability of different precipitation datasets with GPCC. In the absence of GPCC data, this comparison will be useful for conducting such studies. In addition, monthly precipitation data set for the same period from 58 meteorological stations of Pakistan Meteorological Department (PMD) are also used to analyze the precipitation and drought events. PCA method is adopted to segregate GPCC gridded precipitation of SCA into sub-regional scale using Varimax rotation as suggested by Malik et al. (2013). According to Kaiser (1958, 1959), Varimax rotation on each factor of the variables reduces large number small loading and vice versa. Moreover, it simplifies the interpretation. PCA is oftenly used to reduce the number of variables in the data (Bryan, 1994). The factor analysis forms different groups of data by applying on time series of precipitation data at each grid point and each group has the same characteristics (Thurstone, 1931). The data reduction and structure detection are the prime purposes of using PCA in this study, carried out by statistical package for the social sciences (Nie, 1968).

Time series of percent of normal rainfall is calculated over the whole SCA region including Pakistan's. This helps to investigate the precipitation amount during drought years. Groups having same precipitation characteristics are plotted together.

a. Rainfall variability index (RVI)

According to Gocic and Trajkovic (2013b), rainfall variability index (δi) is calculated as

$$\delta i = (Pi - \mu)/\sigma \qquad (1)$$

Where δi is rainfall variability index for year i, Pi is annual rainfall for year i, μ and σ are the mean annual rainfall and standard deviation for the period of 1951-2010. Time series of rainfall are classified into different climatic regimes. Incase δ is negative, then the year is said to be drought year. According to World Meteorological Organization (WMO, 1975), rainfall time series can be classified into different climate regimes.

$$\left.\begin{array}{ll} P < \mu - 2.\sigma & \text{exterme dry} \\ \mu - 2.\sigma < P < \mu - \sigma & \text{dry} \\ \mu - \sigma < P < \mu + \sigma & \text{normal} \\ P > \mu + \sigma & \text{wet} \end{array}\right\} \quad (2)$$

b. Deciles Index

Deciles are one particular example of cumulated frequency distribution. Gibbs and Maher (1967) have used decile method to study Australian droughts. In this method, cumulated frequency curve or data array is used to calculate the limits of each decile of the distribution. The first decile represents the amount of precipitation lower than 10 percent of the total, the second decile is the amount not exceeded by 20 percent of the total and so on. The fifth decile or median is the rainfall amount not more than 50 percent of the total. The decile values depict the rainfall distribution, decile range and useful information on departure from normal. The decile ranges are useful in classifying rainfall occurrence (Table 1).

c. Standardized Precipitation Index (SPI)

Mckee et al. (1993, 1995) developed SPI to quantify precipitation deficit on different time scales i.e., 1, 3, 6, 9, 12, 24, and 48 months. The probability on different scale allows SPI to monitor the impact on agriculture and soil moisture over a short time period whereas, reservoirs, water supplies and stream flow over long term. Several studies (e.g., Gocic and Trajkovic, 2014; Heim, 2002; Keyantash and Dracup, 2002) ranked SPI at the top of all drought indicators due to its flexibility and feature. It is one of the mostly used drought indicator worldwide (WMO, 2012). Long term sequence data of precipitation at least 30 years are required to calculate SPI at any location, however, longer data is preferable (Hayes et al., 1999; Seiler et al., 2002). The drought classification by SPI and probability is shown in Table 2.

Five statistical tests are used on annual precipitation, namely; t-Student's test, Mann-Kendal test (Mann,1945; Helsel and Hirsch,1992; Maidment,1993) and Spearman's Rho test (Lehmann, 2006; Sneyers, 1990) for linear trend, turning point test (Kotegodda, 1980) for randomness and Sen's Slope test (Sen, 1968) for slope magnitude at α = 0.05 significance level.

The t-Student test statistically verifies by testing the difference from zero of the slope coefficient, whether the correlation coefficient is significantly different than zero. The population correlation coefficient ρ = 0 under the null hypothesis particularly, the equation is computed as:

$$t_c = \frac{\mathrm{r}.\sqrt{N-2}}{\sqrt{1-r^2}} \qquad (3)$$

where r is the sample correlation coefficient and N is the sample size. The null hypothesis is rejected on the basis of a two-tailed tests at significance level α if $|t_c| \geq t_{1-\frac{\alpha}{2}}(N-2)$ where $|t_1| \geq t_{1-\frac{\alpha}{2}}(N-2)$ is the value drawn from a Student's t distribution with $N-2$ degrees of freedom and non exceedence probability (1-α/2). Values of α are normally 10, 5, 2.5 and 1 percent.

The linear trend of monthly, seasonal and annual precipitation and temperature are calculated using Mann Kendal test, which has been broadly used to analyze the long term climatological and hydrological time series. The variance of the equation is calculated by using the following equation.

$$Var(S)=\frac{1}{18}\left[n(n-1)(2n+5)-\sum_{p=1}^{q}t_p(t_p-1)(2t_p+5)\right] \tag{4}$$

Where q is the number of tied groups (having the same value of sample data set) and tp is the number of data values in the p^{th} group.

The test statics S is given by:

$$S=\sum_{j=1}^{n-1}\sum_{k=j+1}^{n}\operatorname{sgn}(x_k-x_j) \tag{5}$$

Where x_k and x_j are the sequential data values, n is the length of data set and sgn (θ) is the sign function that is equal to 1, 0, -1, if θ is greater than equal to or less than zero, respectively.

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

The value of Z is approximately normal distributed and positive value of Z greater than 1.96 represents the significant increasing trend, whereas negative value lower than -1.96 donates a significant decreasing trend at 95% significance level with two tailed tests. The values of Z greater than 1.69 and less than -1.69 shows significant level ($\alpha = 0.05$) with one tailed test.

Non parametric method proposed by Sen (1968) is used to determine the true slope (change per unit time) when time series shows linear trend. This means that *f (t)* in the equation given below is equal to

$$f(t) = Qt + B \tag{7}$$

where Q is the slope and B is a constant.

This method estimates the magnitude of trend as follows:

$$\mathrm{Q} = median\frac{x_j - x_k}{t_j - t_k} \qquad (8)$$

where x_j and x_k are the data values at times t_j and $t_k(j > k)$, respectively.

Spearman Rho test (r_s) identifies the strength between the two variables ranges from -1 to +1. A positive values of $r_s = +1$, shows perfect positive corealtion and vice versa, where as $r_s = 0$ indicate no association between the rank. The values of r_s can be determined by the following equation.

$$r_s = 1 - \frac{6\sum D^2}{N^3 - N} \qquad (9)$$

Where r_s is spearman corealation cofficinet, D is the difference between the ranks and N is the number of rank. The values of $p < 0.05$ is said to be statistically significant.

The turning point test is based on counting in a series X_t (t = 1, 2 ….N) the number of turning points m , i.e. for each t = 2, 3 …, N-1, the values for which X_t is larger than X_t -1 and X_t +1 or X_t is smaller than X_t -1 and X_t +1 (Kottegoda, 1980).

Under the null hypothesis the series is assumed random and it can be shown that the statistic

$$Z_c = \frac{[\mathrm{m} - \mathrm{E(m)}]}{\sqrt{\mathrm{var(m)}}} \qquad (10)$$

$$E(m) = \frac{2.(\mathrm{N} - 2)}{3} \qquad (11)$$

$$var(m) = \frac{(16.\mathrm{N} - 29)}{90} \qquad (12)$$

converges to a standard normal variable. Then, the null hypothesis is rejected with a significance level α if $|z_c| \geq z_{t_{1-\alpha/2}}$, where $z_{t_{1-\alpha/2}}$ is a standard normal variable corresponding to a non exceedence probability (1-α/2).

The bold character represents the significance trend which is identified by these four statistical methods i.e. student's t-test, Mann-Kendal, Sen's slope and Spearman's Rho (Table 6).

3. Results and Discussions

Four different precipitation datasets (GPCC, CRU, Precip_L, UDEL) with horizontal resolution (0.5°×0.5°) and their ensemble mean were taken to determine the correlation between them on an annual basis (1951-2010) over the domain (20.25°N to 40.25°N and 60.25°E to 80.25°E). The main idea was to determine the precipitation relationship between GPCC and different datasets as rest of the datasets may be used in the absence of GPCC. Since GPCC has a very strong correlation with area weighted station rainfall data of Pakistan. Based on linear and nonlinear regression method, it is noted that GPCC data has a very strong correlation with UDEL (R^2 = 0.968), Ensemble (R^2 = 0.887), Precip-L (R^2 = 0. 759) and CRU (R^2 = 0.706) respectively (Fig.2(a-d)). The polynomial cruve line is useful for analyzing the large data which has more fluctuation and provides the highest values of R^2 shows good fit to the line of data (Carter and Robortson, 1998). The linear trend does not provide the highest values of R^2 as the data was more spread and highly fluctuating. So, we used non linear third order polynomial regression method for Precip_L and CRU data to obtain best fit curve and result are significantly improved. These all are gauged data sets but the variation in the coorealtion is due to regional variation in topography significantly affect the amount of precipition. The nature of precipitation and its uncertainty in distribution, amount, intensity and limitation of observational stations makes it most challenging parameter. According to Schneider et al. (2014), the variation or shortcoming regarding precipitation data is due to inhomogeneous coverage over space and time alongwith the quality control of the station met data. Moreover, the frequent and different kinds of error makes the variations in the data sets as compared to GPCC, which has good spatial coverage with maximum number of station data (more than 51000) and quality control. Therefore, it is preferred for research in the absence of station data.

The spatio-temporal analysis of GPCC gridded data ($0.5^{\circ} \times 0.5^{\circ}$) and Area Weighted Rainfall (AWR) of station in Pakistan are plotted in Fig.3(a and b). Thiessen Polygon Method (1911) was employed to calculate the area factor on PMD station data . As suggested by Rhynsburger (1973), it is commonly used in the fields of meterology and hydrology. According to Fiedler (2003), the station weight is scalar unit and it transforms the point precipitation of gauging station into mean associated precipitation of a region. The analysis shows that the actual observed precipitation was slightly higher than the GPCC precipitation in certain years during 1951-2010 but the trend and variability were same. However, the variation in both datasets was more during 1951-60 since the PMD data of only 41 stations was available at that time. Later, the number of stations reached up to 52 due to which, the time series analysis are very close to each other. This indicates that the strengthening of station network enhances the relationship between the two datasets. Moreover, the spatial analysis reveals that there is a high correlation ($R^2 = 0.93$) between the two datasets. Also, the GPCC data is very close to real time station data, hence, may be used in the absence of station data in Pakistan.

The technique of PCA is applied to time series of all grid points of SCA region precipitation data of GPCC ($0.5^{\circ} \times 0.5^{\circ}$). Six groups were identified and each group has same precipitation characteristics (Fig.4). The first group (A-1) is highly correlated than A-2 with respect to precipitation at grid point and so on. The factors are successively extracted and variance became less and less after six groups.

Fig.4, group A-1 covers most parts of Pakistan and western India and includes agricultural plains, forest, desert and some hilly region. The agro-climatic classification shows that 75 to 88% of the land of this region lies between arid to semi arid (Sajjad and Adnan, 2014). A-2 includes the southwestern parts of Pakistan, Iran and southern Afghanistan, which is largely covered with deserts, rocks and rough surface. A-3 includes the central Asian region mainly consisting of mountains, rocks, steppe and arid lands. A-4 region includes the northeastern parts of India, consisting of plains and high Himalayan foothill ranges. A-5 region covers most part of west of China and east of central Asia, which consist of high mountains (Karakoram), glaciers and barren rocks. A-6 includes extremes of northwest Pakistan and northern Afghanistan where snow covered mountains (Hindu Kush), barren hills and high elevated valleys are found.

a. Analysis of precipitation

The monthly precipitation climatology of each group was plotted over the whole domain (Fig.5). The main objective was to separate the precipitation influencing system in these regions, i.e. southeast monsoon (June, July, August, and Septeber (JJAS)) and western disturbances (December, January, February, and March (DJFM)).

The same colour pattern represents the monthly climatological precipitation behavior in each region. Region A-1 and A-4 are termed as the monsoon dominated regions, where the average daily precipitation varies from 0.82 to 1.68 mm day^{-1}and 2.55 to 7.79 mmday^{-1} respectively, with July is the peak month of precipitation. A-2, A-3 and A-5 were known to be the western disturbances (WDs) dominant regions where the daily average precipitation varies from 0.58 to

0.98 mm day^{-1}, 0.98 to 1.79 mm day^{-1}and 0.25 to 0.61 mm day^{-1} respectively, with February and March are the peak months. A-6 region and Pakistan receives precipitation both; in summer and winter, where the daily averaged amount of precipitation varies (0.53 to 0.98, 1.25 to 3.19) mm day^{-1}during the monsoon and (0.99 to 2.54, 0.68 to 1.67) mm day^{-1}during WDs respectively.

The time series of percent of normal of those regions which have same weather pattern and rainfall characteristics were analyzed together (Fig.6). The percent of normal rainfall was less than 60% in A-2, A-5 and Pakistan, which caused drought during 1971, 2000, 2001 and 2002 in these regions.

Time series analysis of annual rainfall variability index (ARVI) and percentage distribution of extremely dry, dry, normal and wet years were calculated for the SCA region (Figs.7 and 8) respectively. According to ARVI, the longest driest long period was from 2000 to 2002 in the whole SCA region, while the extremely dry years were 1971, 2001 and 2002 in A-3 and A-6. The percentage distribution of dry years in A-4 region was much higher than the rest, as the rainfall variablitiy of summer monsoon rainfall has lot of impacts in this region.

The summary of statistical parameters of monthly precipitation during 1951-2010 of SCA region is shown in Table-4. The mean monthly precipitation is ranged from 12.32 mm to 72.58 mm with highest maximum value 340.28 mm in the region A-4 and lowest minimum value 0.0 mm over Pakistan. The highest values of coefficient of variation (CV) of the precipitation value were observed in the A-2 region at the rate of 83.31%, while the lowest CV of 44.32% at A-1.

b. Analysis of Drought

The first decile represents the amount of precipitation lower than 10% of total precipitation and it depicts clearly below normal rainfall, which leads to intense droughts. The analysis shows that the decile was lowest during 2000 over the whole SCA region, where as intense drought conditon was reported in most part of SCA region during 1970 and 2010 (Fig.9). The intense drought was reported due to below normal rainfall (decile-1) during the two decades i.e. 1971-80 and 2001-10. It is also noted that intense drought years were reported in all regions during 2001-10. The maximum number of intense droughts were detected in A-2 region during the same decade, while region A-1 was most vulnerable, where almost one intense drought was reported in each decade except during 1991-2000 (Fig.10).

The SPI on 3, 6, and 9 months are used to determine droughts on a shorter time scale affecting the agricultural practices of a region (Paulo and Pereira, 2008). The 12-month time scale SPI is more suitable to determine the dry periods and helpful for water resources management (Raziei et al., 2009). The time series of SPI-12 are plotted over six groups during 1951-2010 as shown in Fig.(11).

The maximum number of total droughts were observed in region A-5 with 4 severe droughts during the 60 years (1951-2010). The most severe droughts were reported during 2000 to 2002 in the SCA region except for Pakistan, where it was moderate. The drought of 1952 was the most severe in Pakistan. The drought characteristics at 12-month time scale in the whole SCA region during 1951-2010 are presented in Table 3.

The maximum percentage of mild drought was reported in region A-4 and A-5 while the moderate drought was observed in regions A-1, A-5, A-6 and Pakistan. The maximum severe droughts were reported in region A-5, while the extreme was reported in A-2, A-3 and Pakistan, but these droughts were less frequent than the other classes as discussed by Moreira et al. (2008).

The regions A-2, A-3 and Pakistan experience all types of droughts; from mild to extreme while the maximum total number of droughts were observed in region A-5 (Fig.12).

c. Trend Analysis

The time series analysis of RVI, SPI at the 12 month time scale and percent of annual normal rainfall were calculated (Fig.13). The intense droughts were reported when percent of normal rainfall was below 80% observed in the whole SCA region. A strong correlation among the three indices has been observed as RVI to 12-SPI ($R^2 = 0.85$) and percent of annual normal to 12-SPI ($R^2 = 0.88$). So, we may conclude that all three indices are directly proportional to each other. Moreover, this is a very good indicator to monitor drought in a region.

The results of trend analysis are summarized on monthly precipitation over the period 1951-2010 using the Mann-kendal test at different significance levels (Table-5). The bold values represent the trend at different significance levels with two tailed tests. It is noted that month of June and Septemeber shows increasing trend of 2.03 and 2.09 mm/month in A-5 and A-3 regions, respectively. Simialry, significant increasing trend was observed during June (4.08 and 4.03) mm/month in A-6 and Pakistan region. However, a significant decreasing trend was detected in January and August (-2.02 and -2.48) mm/month in region A-4, at $\alpha = 0.05$ significance level.

The annual trend of precipitation obtained by five statistical methods is given in Table-6. The t-student test shows that a significant linear trend is present (increasing in A-5 and Pakistan region and decreasing in A-4 region). The turning point test results depicted that the null hypothesis is accepted as data series is random in whole SCA region. These results of Mann-kendal and Sen's slope show a significant ($\alpha = 0.05$) increasing trend in annual precipitation time series in region A-5 and Pakistan with a slope of 0.75 mm/year and 1.71 mm/year, respectively. Besides, only region A-4 has significant decreasing trend with a slope of -2.15 mm/year.

The decadal anomaly shows decreasing trend in SCA region. All the regions except A-5 and Pakistan show increasing trend (Fig.14). The precipitation in region A-1 suggests that monsoon rainfall has increased in the last decade (2001-2010). The precipitation in region A-5 has increased may be due to high intensity of WDs in the extreme north of that region. In addition, the whole region experienced negative anomaly in annual precipitation during 1984, 2000 and 2001(the lowest). The maximum positive anomaly was observed in the whole SCA region except for region A-1 during 1957. The highest decadal positive anomaly was recorded 0.09 mm/day in region A-1 during 2001-2010, 0.04 mm/day in A-2 (1951-60 and 1991-2000) 0.04 mm/day and 0.21mm/day in A-3 and A-4 during 1951-60 and 0.08, 0.09 and 0.13 mm/day in regions A-5, A-6 and Pakistan during 1991-2000, respectively. The highest decrease in precipitation was observed in A-4 region (-0.20 mm/day) during 2001-10. The trend in decadle precipitation was negative in 67% part of SCA region during the three consecutive decades (1961-70, 1971-80, 1981-90) and 2001-10. Moreover, the positive trend in decadle precipitation was observed during 1951-60 and 1991-2000.

4. Conclusions

This research work was carried out to differentiate precipitation and its trend on monthly, annual and decadal base along drought behavior and its characteristics during the past 60 years (1951-2010) in SCA region with special focus on Pakistan. Five different statistical tests were applied at different significance levels. Besides, different drought indices, namely; rainfall variability index, percent of rainfall, deciles and SPI were estimated. The spatio-temporal analysis of GPCC precipitation showed a high correlation (R^2 = 0.93) with area weighted station precipitation of Pakistan as well as the other gridded data. Moreover, it was identified that increase in number of synoptic stations strengthens the correlation.

The climatological patterns illustrate that the two precipitation weather system (monsoon and western disturbances) effect the regions (A-1 and A-4) and (A-2, A-3 and A-5) respectively. However, region A-6 and Pakistan receive rainfall in both weather systems. According to these investigations, two main drought periods were identified (1971 and 2000-2002), whereas the extremely dry year was 2001 in SCA region. In Pakistan, the most severe drought was recorded in 1952, while the episode of long drought was experienced in 2000-2002. The region A-5 is the most vulnerable towards drought. The monthly precipitation analysis suggests that the increasing trend was observed in September and June in regions A-3 and A-5 respectively. However, a significant decreasing trend is noted in January and August in A-4 region. In addition, an annual analysis suggests a significant increasing trend in the region A-5 and Pakistan, while decreasing over region A-4.

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Table 1: Classification of drought based on deciles index

Departure	Decile Range	Percent	Status
Very much above normal	10	Highest 10	Intense Wet
Much above normal	9	80-90	Severe Wet
Above normal	8	70-80	Moderate wet
Slighlty above normal	7	60-70	Mild wet
Normal	5 and 6	Middle 20	Normal
Slightly below bormal	4	30-40	Mild drought
Below normal	3	20-30	Moderate drought
Much below normal	2	10-20	Severe drought
Very much below normal	1	Lowest 10	Intense drought

Table 2: Drought classification by SPI values and corresponding events probability

SPI Values	Category	Probability%
2.00 or more	Extremely Wet	1.7
1.50 to 1.99	Severe Wet	2.7
1.00 to 1.49	Moderate Wet	9.1
0.50 to 0.99	Mild Wet	16.5
0.49 to -0.49	Normal	40.0
-0.50 to -0.99	Mild Drought	16.5
-1.00 to -1.49	Moderate Drought	9.1
-1.50 to -1.99	Severe Drought	2.7
-2.00 and less	Extremely Drought	1.7

Table 3: Drought Characteristics at 12-Month Time Scale SPI

	The most severe drought		Number of drought years during the observed period			
Regions	12-SPI	Year	Mild	Moderate	Extreme/Severe	total
A-1	-1.91	2001	11	4	1	16
A-2	-2.1	2000	10	2	4	16
A-3	-2.14	2001	9	3	3	15
A-4	-1.73	2002	12	2	3	17
A-5	-1.76	2001	11	4	4	19
A-6	-1.98	2002	10	4	3	17
Pak	-2.23	1952	11	4	3	18

Table 4: Statistical parameters of Monthly Precipitation during 1951-2010 of SCA region

Regions	Min (mm)	Max (mm)	Mean (mm)	Standard deviation(mm).	CV(%)	Skewness	Kurtosis
A-1	0.20	290.61	45.38	20.11	44.32	1.06	4.68
A-2	0.07	83.21	12.32	10.26	83.31	0.62	-0.49
A-3	0.58	97.03	23.63	10.22	43.24	0.58	-1.71
A-4	0.31	340.28	72.58	29.28	40.34	-0.30	-0.31
A-5	0.41	57.87	13.40	8.09	60.32	0.79	0.48
A-6	1.02	211.79	36.83	22.12	60.05	1.43	6.14
Pak	0.00	198.98	41.12	20.93	50.90	-0.10	-1.12

Note:CV- Coefficient of Variation.

Table 5: Mann-Kendal Trend of Monthly Precipitation (mm) at different significance level α = 0.1, 0.05, 0.01, 0.001.

	A-1	A-2	A-3	A-4	A-5	A-6	Pak
Jan	-0.44	-0.29	-0.11	**-2.02***	1.41	0.02	0.48
Feb	1.52	0.04	-0.30	**1.69**$^{+}$	**1.75**$^{+}$	1.21	**1.85**$^{+}$
Mar	0.06	-0.61	**-1.78**$^{+}$	-0.54	-0.49	-1.22	0.36
Apr	-0.21	**-1.96**$^{+}$	-1.37	0.16	**1.66**$^{+}$	**-1.89**$^{+}$	0.84
May	0.62	-0.80	-1.12	1.19	-0.78	-1.58	0.30
Jun	**1.78**$^{+}$	0.98	0.36	0.96	**2.03***	**4.08*****	**4.03*****
Jul	1.19	0.98	0.87	-0.99	1.58	**-1.72**$^{+}$	1.19
Aug	0.20	-0.78	1.08	**-2.48***	0.98	0.62	1.15
Sep	0.36	1.15	**2.09***	-0.52	1.52	0.99	0.36
Oct	0.52	-0.36	0.26	-0.59	0.36	0.15	-0.20
Nov	0.75	0.71	-0.27	0.29	0.36	0.34	0.78
Dec	0.15	-0.43	0.67	-0.34	0.21	-0.08	-0.15

Significance level: + for α =0.1, * for α =0.05, **α =0.01 and * α=0.001**

Table 6: Results of the statistical tests for the annual precipitation over the period 1951-2010

Test Name	Symbol	A-1	A-2	A-3	A-4	A-5	A-6	Pak
t-Student	t_c	0.98	0.02	-1.48	**-2.12***	**2.81***	0.41	**2.60***
Turning points	Z_C	0.72	0.41	-1.14	1.68	0.10	-1.64	-0.10
Mann-Kendall	Z_S	1.46	-0.26	-1.09	**-2.07***	**2.48***	0.24	**2.39***
Sen's Slope	Q	1.11	-0.05	-0.42	**-2.15**	**0.75**	0.17	**1.71**
Spearman Rho	r_s	0.20	-0.03	-0.14	**-0.26***	**0.33***	0.03	**0.31***
	p	0.13	0.77	0.28	**0.04**	**0.01**	0.83	**0.02**

Bold characters represent trends identified by four statistical methods.
*Statistically significant trends at α=0.05 level of significance

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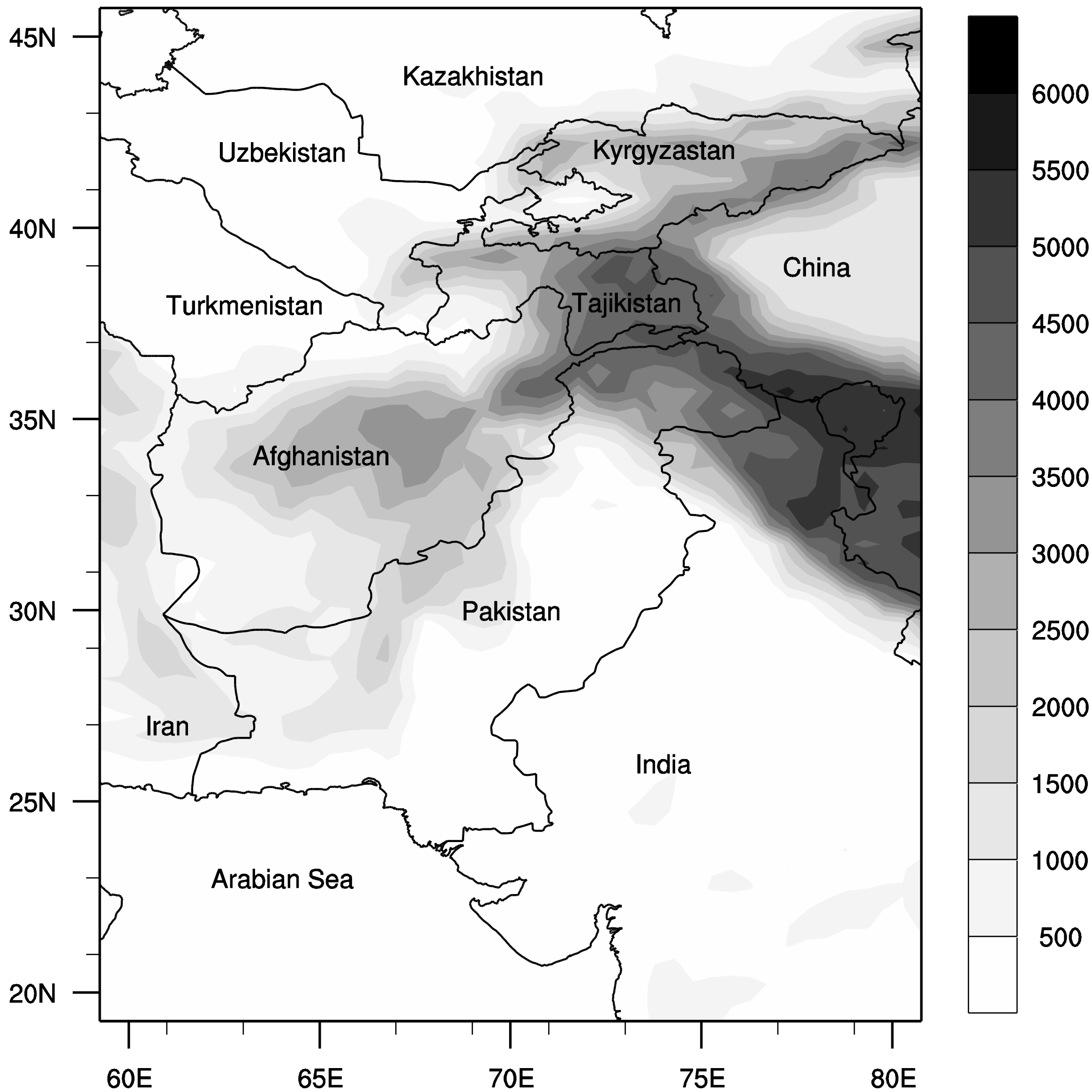

Fig.1: Topographical map of SCA region elevation (meters)

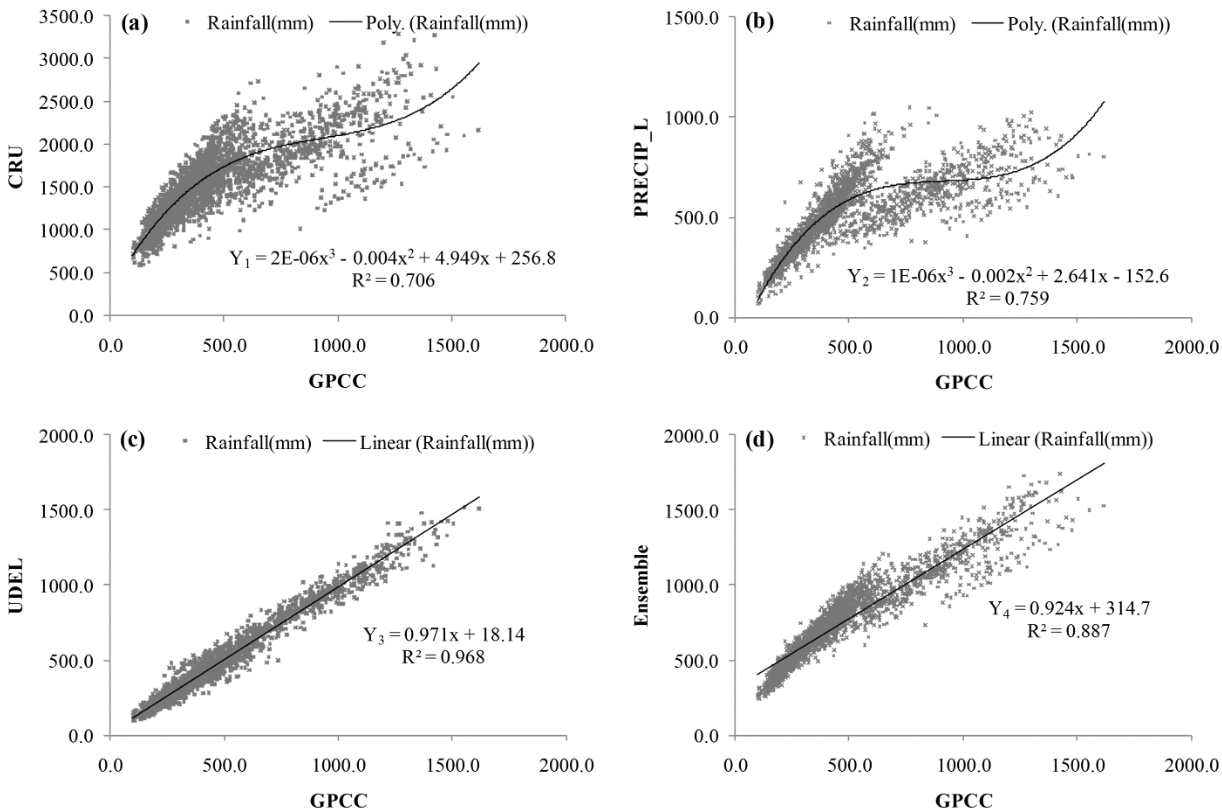

Fig.2(a-d)**:** Correlation of GPCC precipitation data with CRU, Precip-L, UDEL and Ensemble

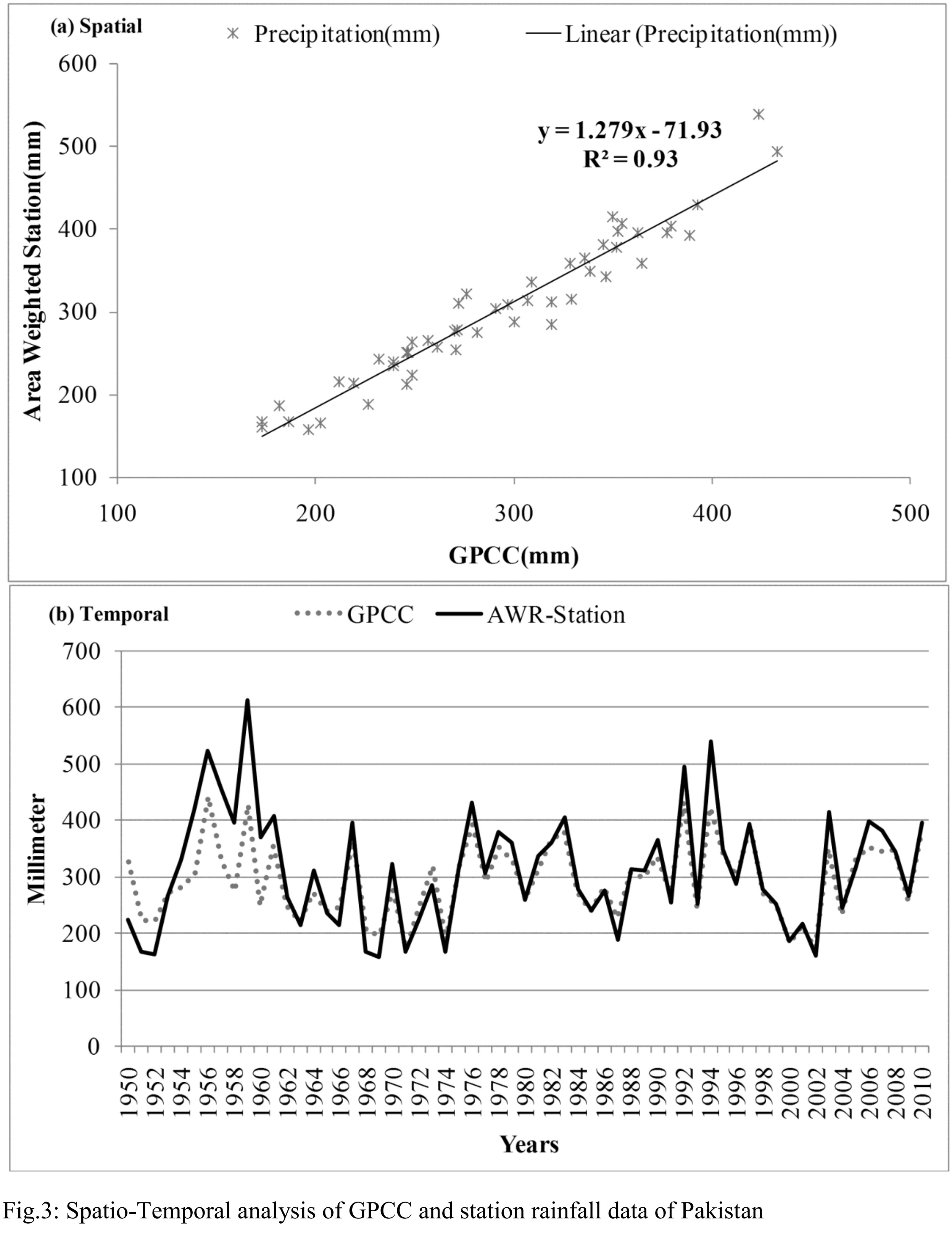

Fig.3: Spatio-Temporal analysis of GPCC and station rainfall data of Pakistan

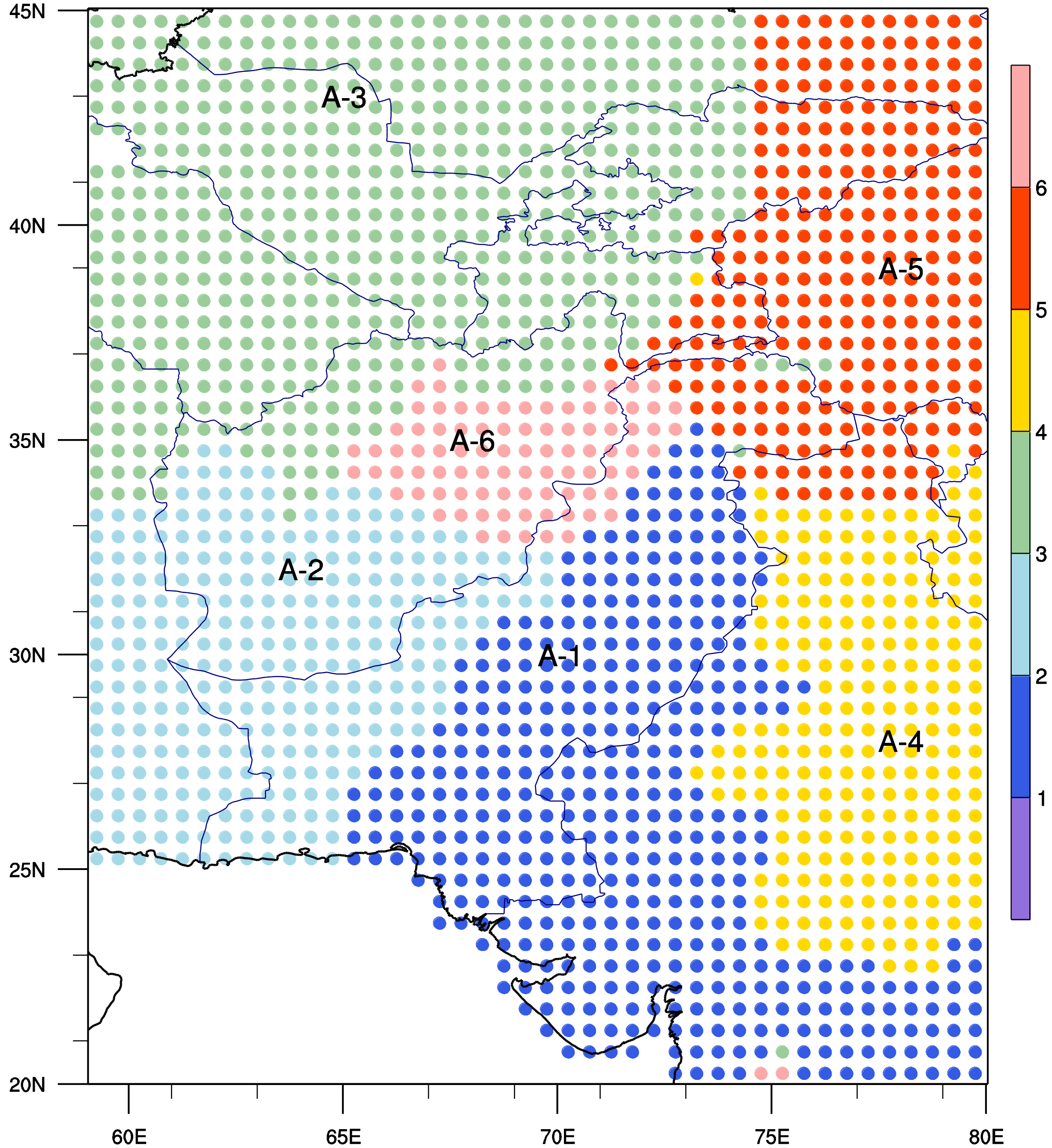

Fig.4**:** Distribution of GPCC precipitation using PCA over the SCA region

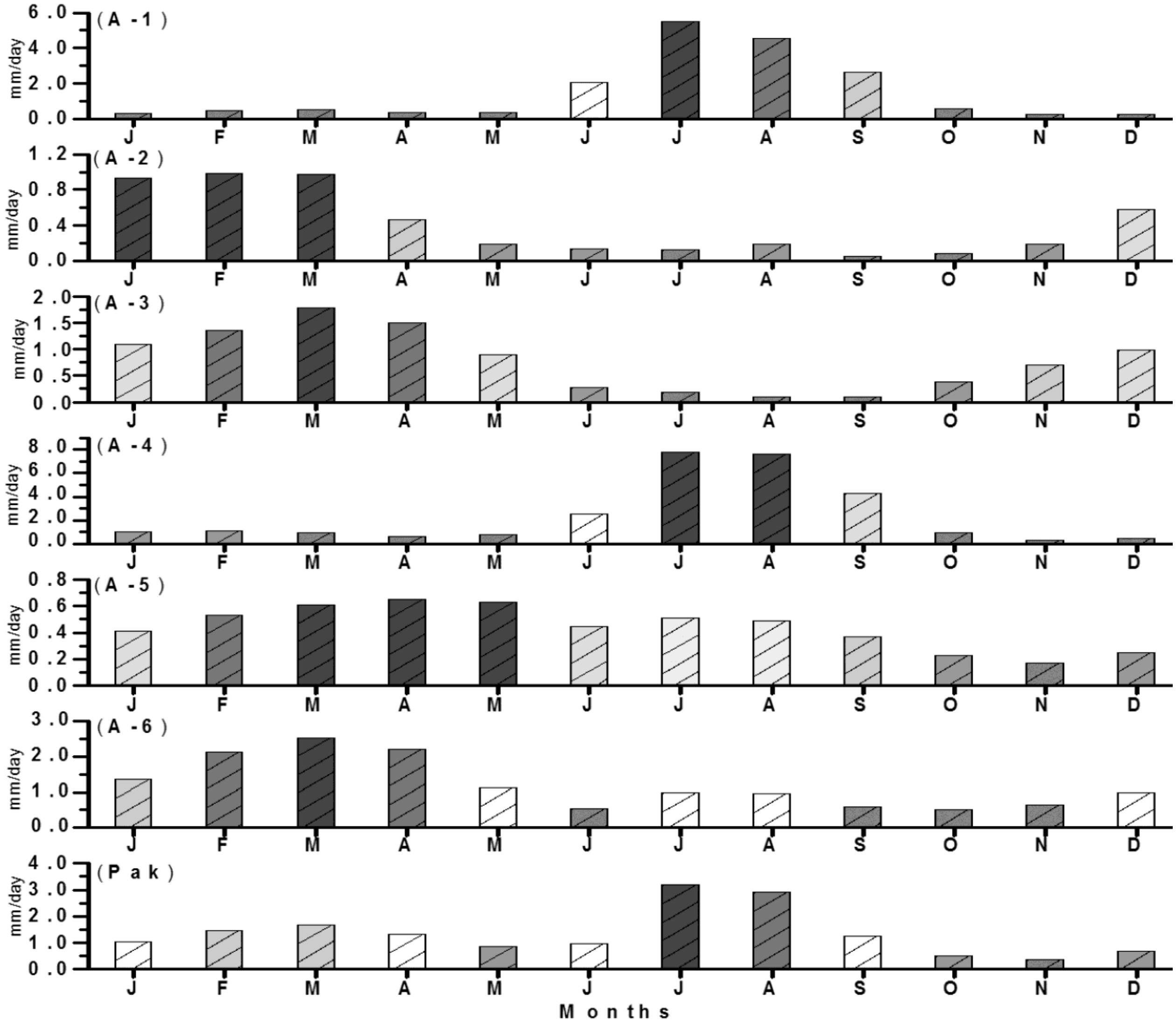

Fig.5: monthly average precipitation and pattern of GPCC in different regions

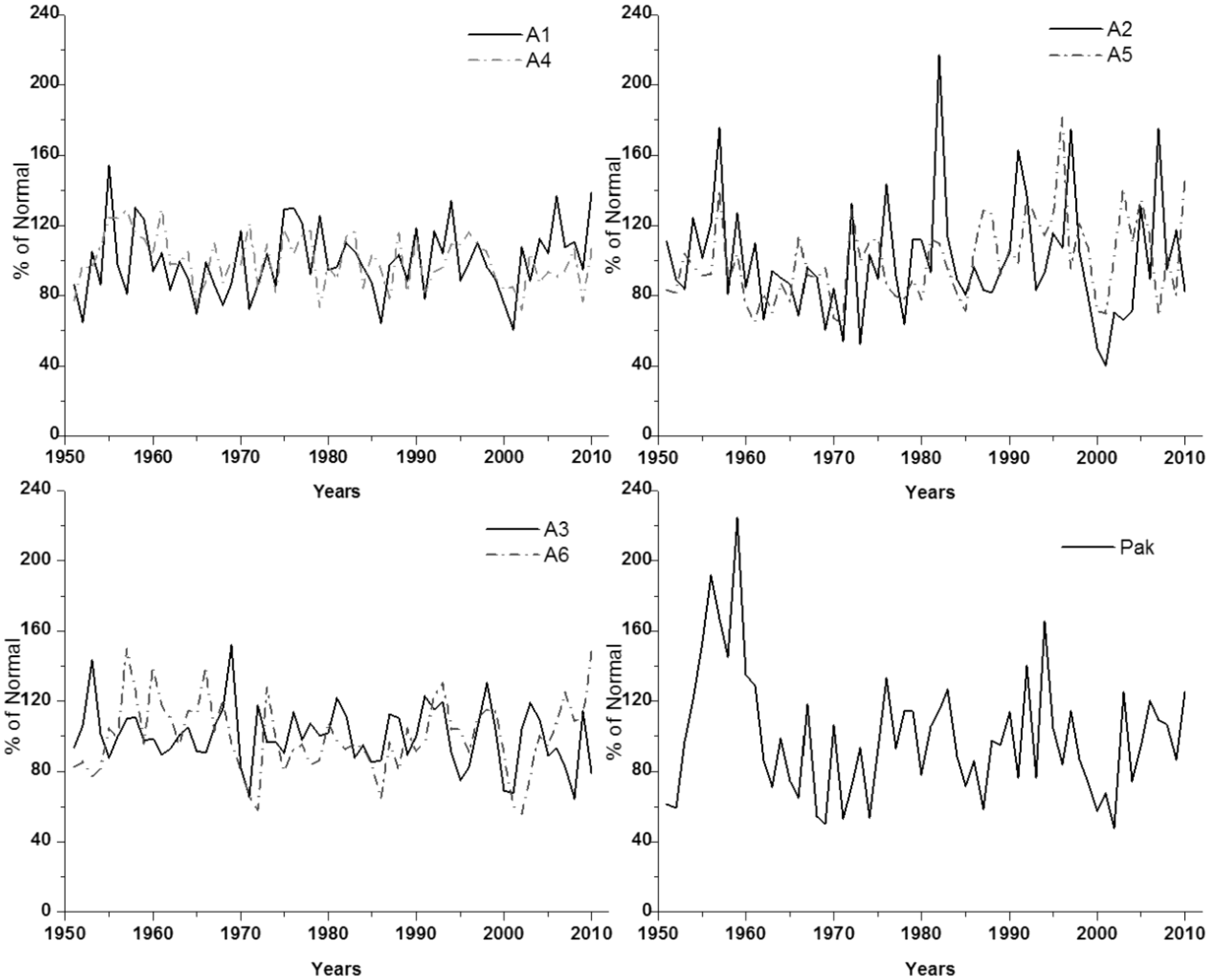

Fig.6: Time series of Percent of Rainfall in the SCA region.

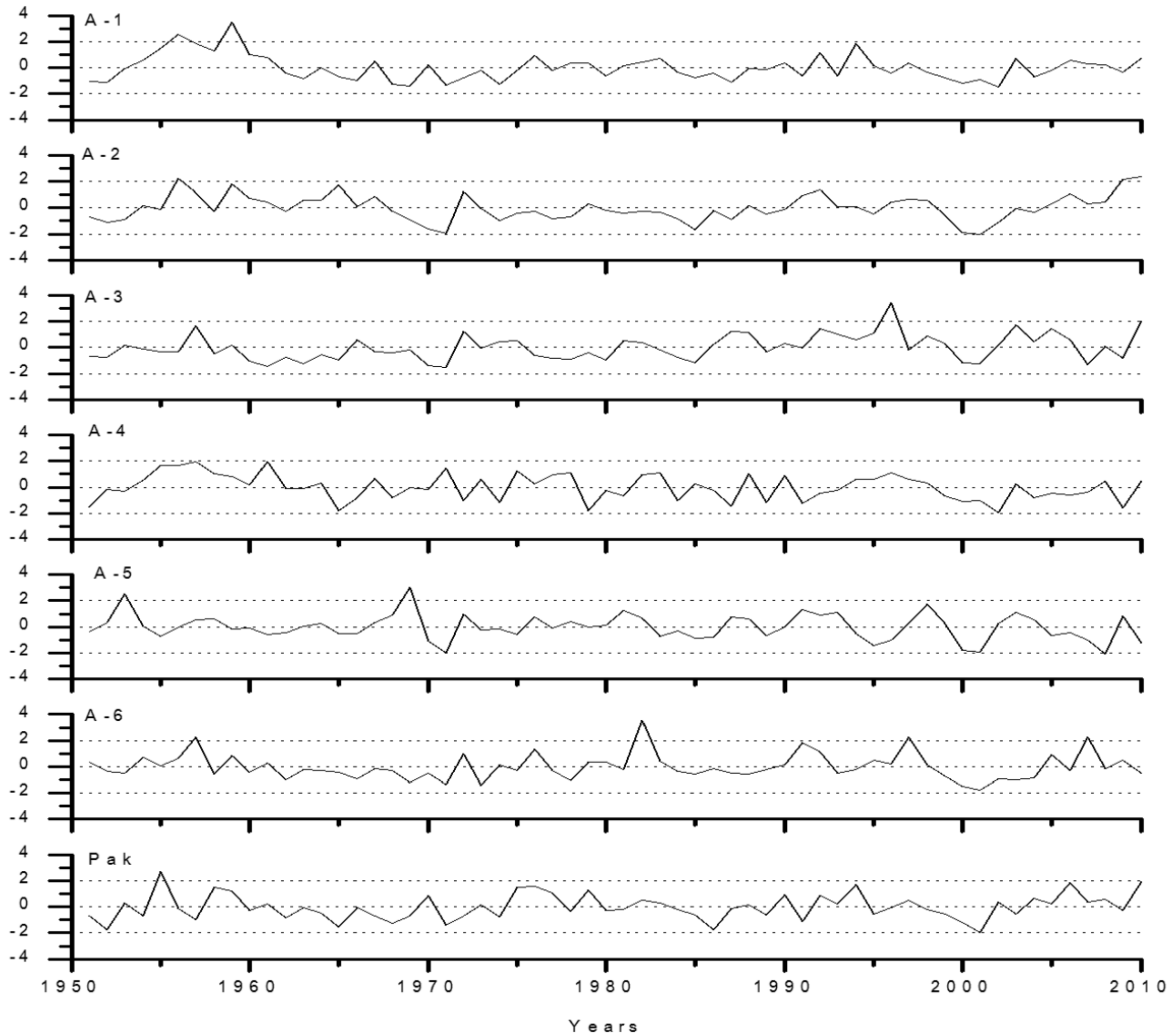

Fig.7: Rainfall Variability Index for the SCA region

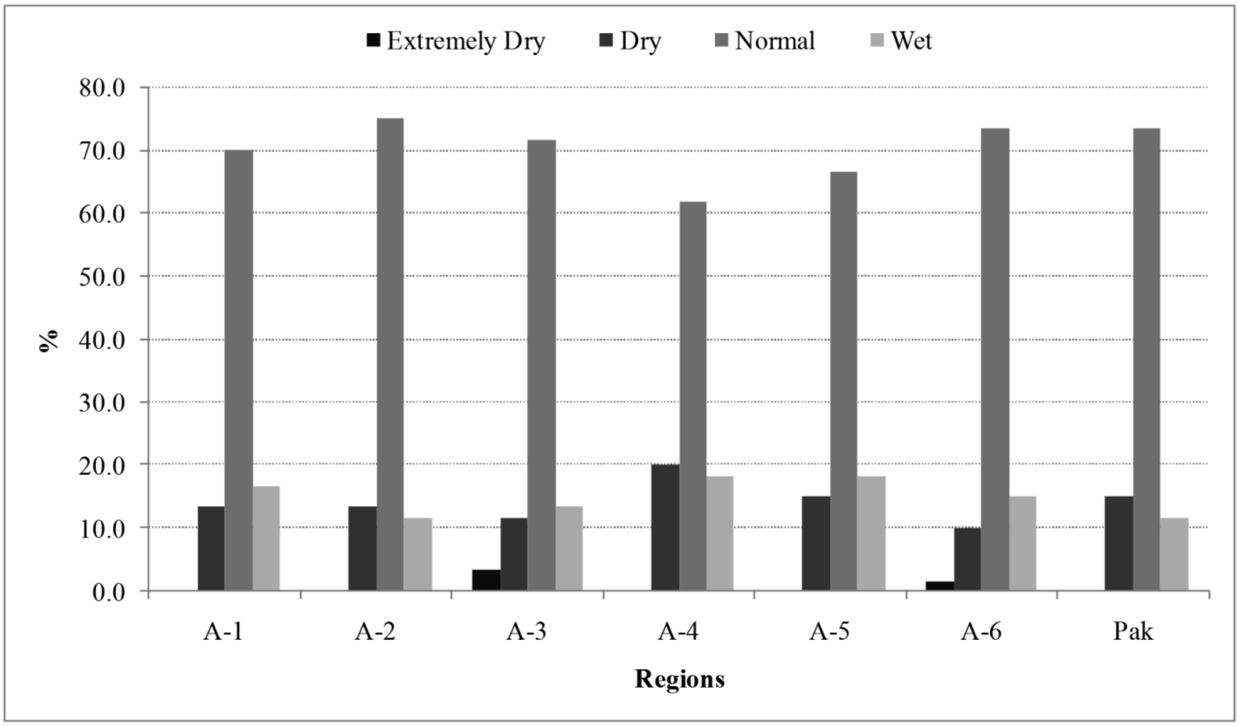

Fig.8: % Distribution of Extremely Dry, Dry, Normal and Wet Years in the SCA Region

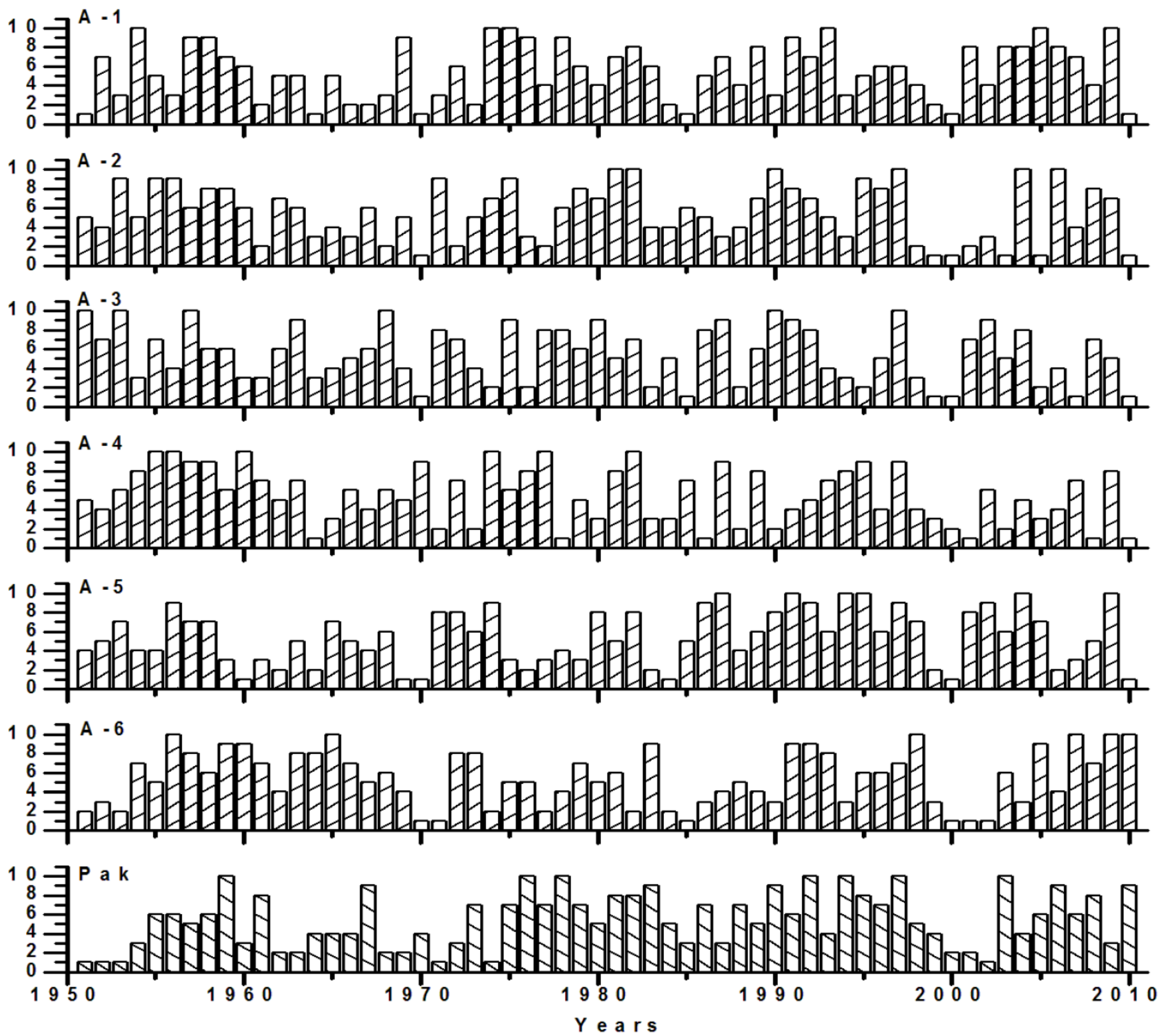

Fig.9: Time series of rainfall deciles in different zones

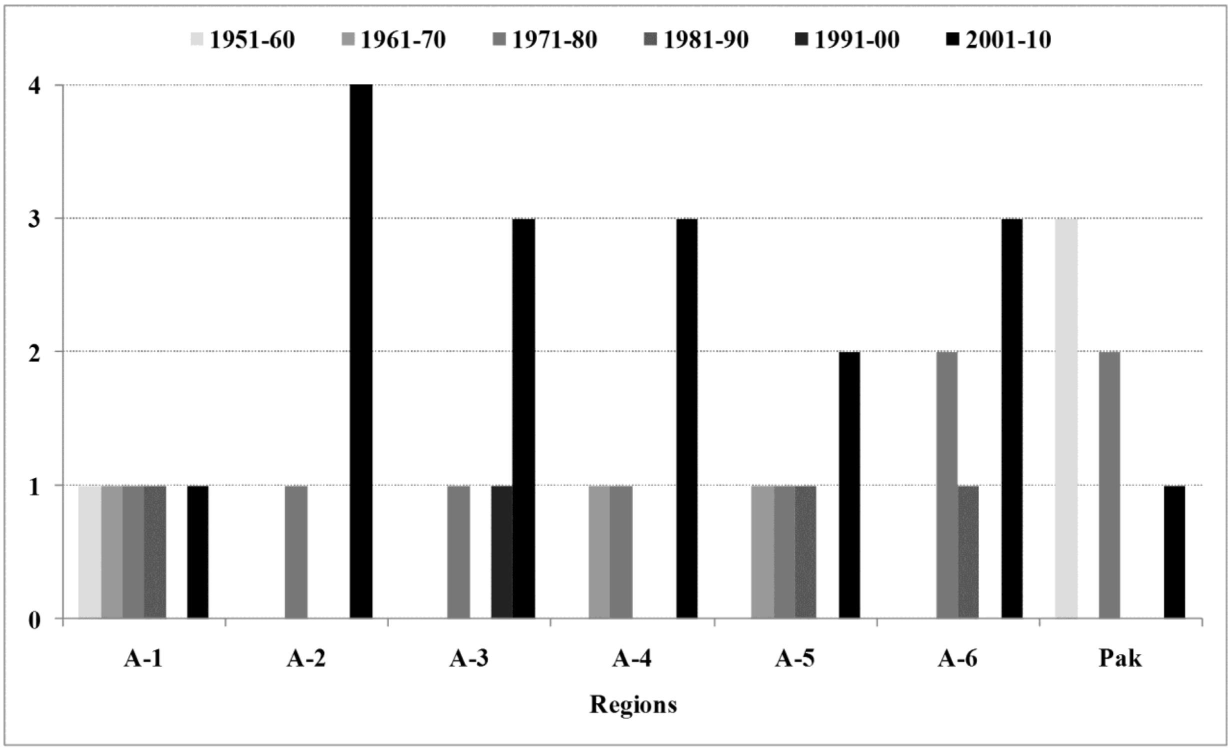

Fig.10: Total Regional Decile-1 on Decadal Basis

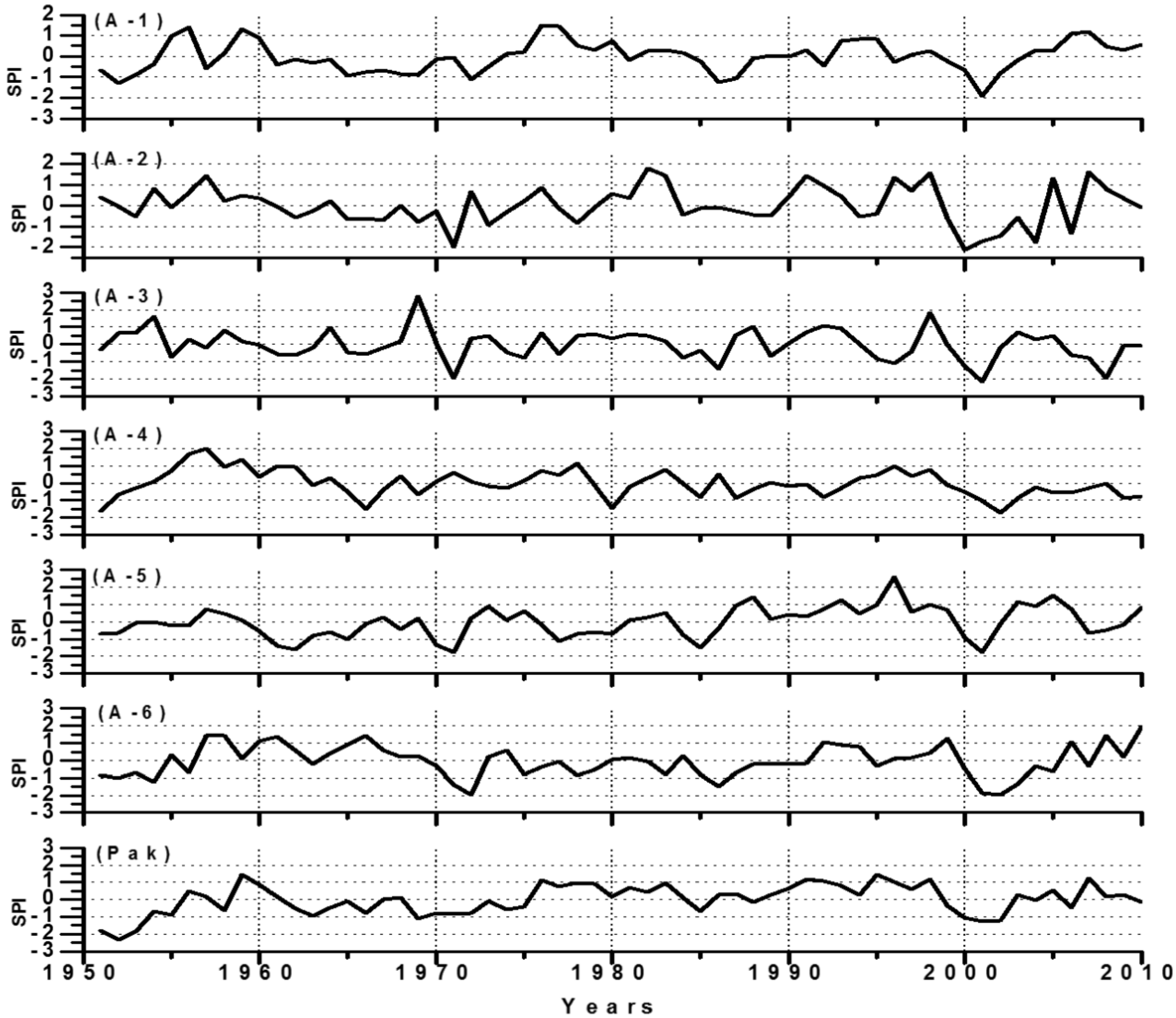

Fig.11: Time series of SPI-12 at different zones.

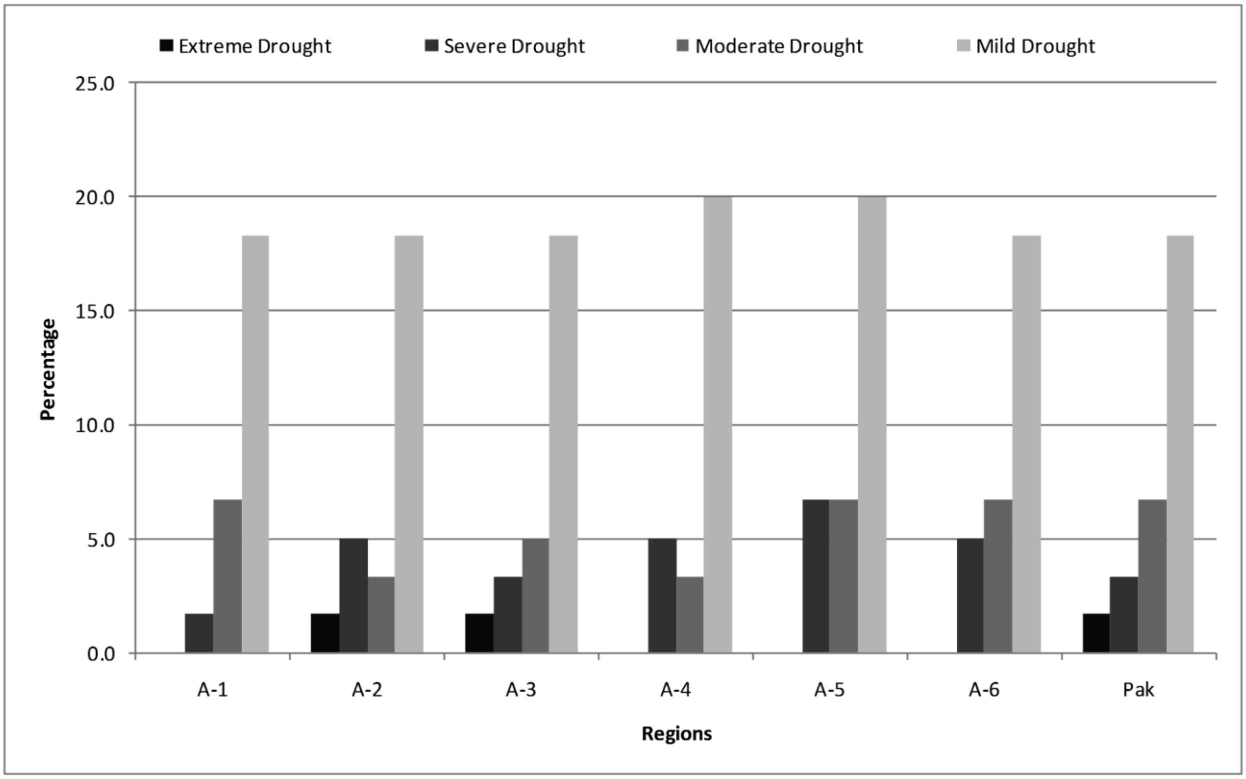

Fig.12: Distribution in Percentage of droughts in the SCA regions during 1951-2010.

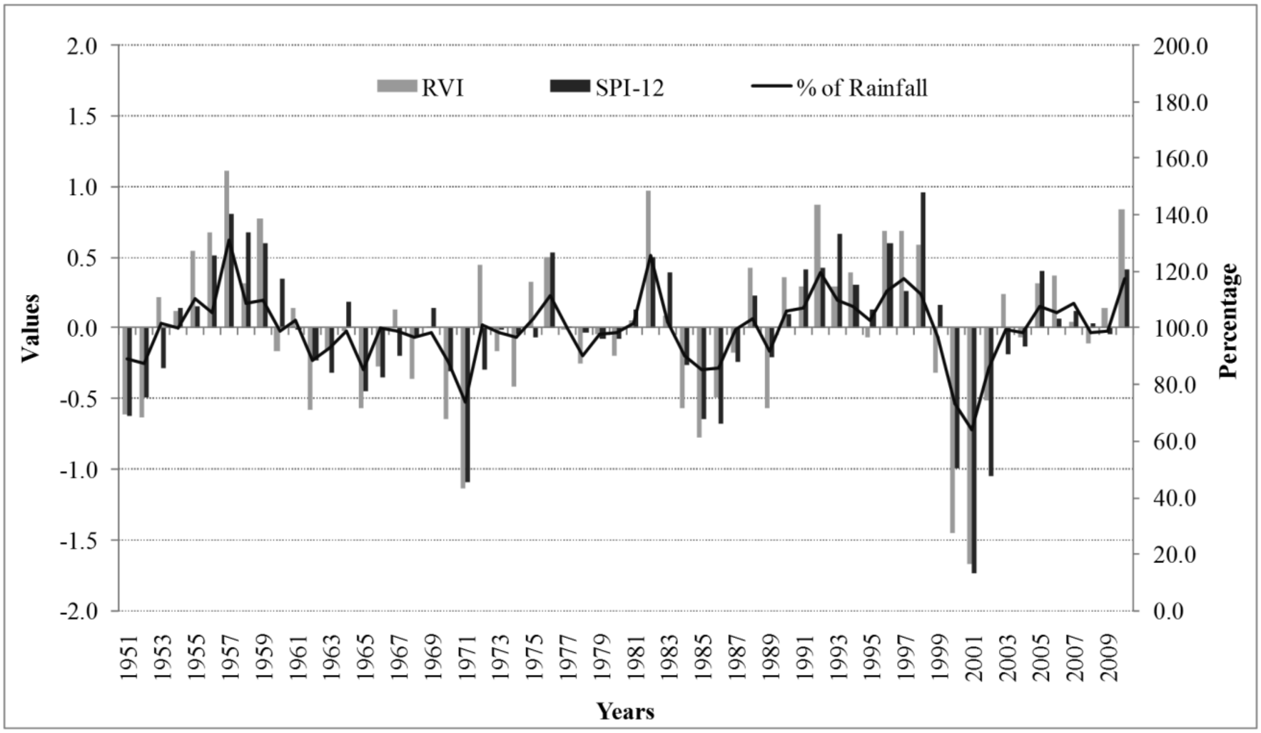

Fig.13: Times series comparison of RVI, SPI-12 and Percent of Normal rainfall in SCA region.

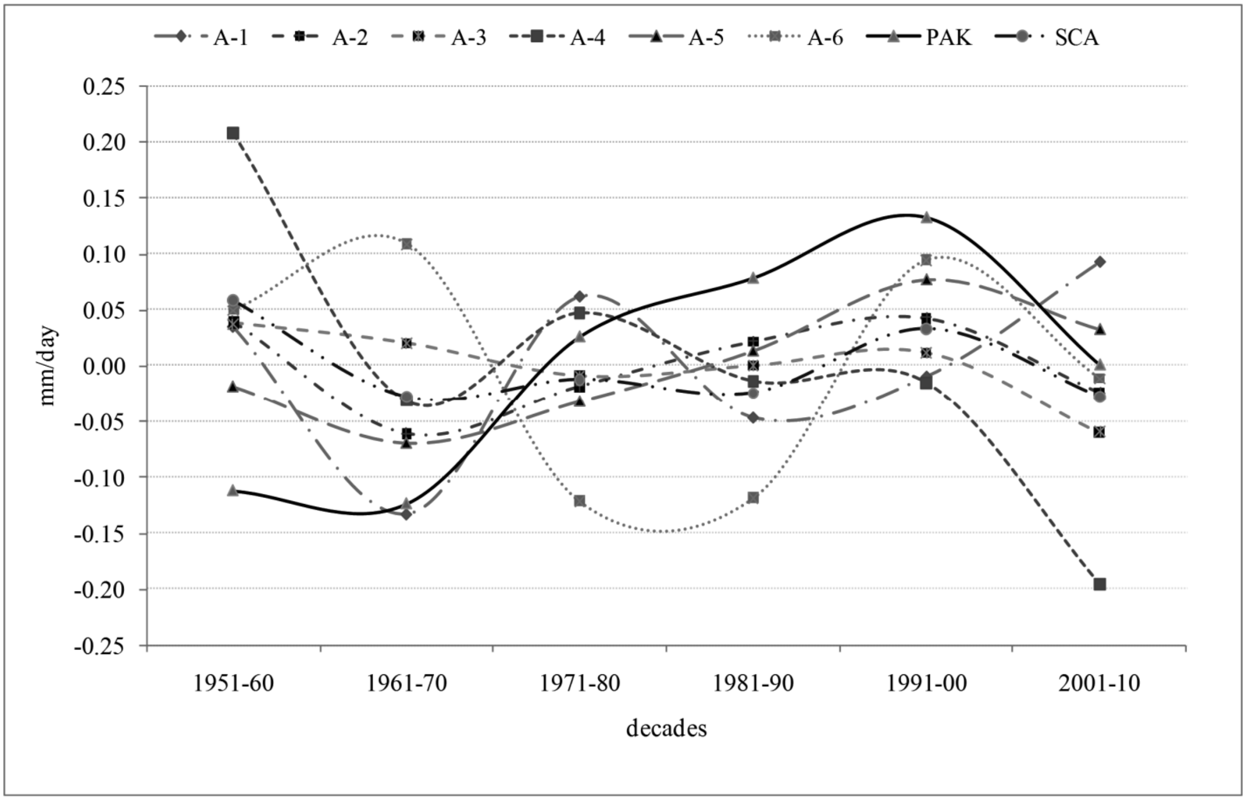

Fig.14: Decadal anomalies of precipitation (mm day^{-1}) in the SCA region.