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ORIGINAL PAPER

Investigation of summer monsoon rainfall variability in Pakistan

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Abstract This study analyzes the inter-annual and intra-seasonal rainfall variability in Pakistan using daily rainfall data during the summer monsoon season (June to September) recorded from 1980 to 2014. The variability in inter-annual monsoon rainfall ranges from 20 % in north-eastern regions to 65 % in southwestern regions of Pakistan. The analysis reveals that the transition of the negative and positive anomalies was not uniform in the investigated dataset. In order to acquire broad observations of the intra-seasonal variability, an objective criterion, the pre-active period, active period and post-active periods of the summer monsoon rainfall have demarcated. The analysis also reveals that the rainfall in June has no significant contribution to the increase in intra-seasonal rainfall in Pakistan. The rainfall has, however, been enhanced in the summer monsoon in August. The rainfall of September demonstrates a sharp decrease, resulting in a high variability in the summer monsoon season. A detailed examination of the intra-seasonal rainfall also reveals frequent amplitude from late July to early August. The daily normal rainfall fluctuates significantly with its maximum in the Murree hills and its minimum in the northwestern Baluchistan.

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1 Introduction

Summer monsoon rainfall is one of the most dynamic parts of the global climate system. Numerous scientists have quantified disparities in summer monsoon rainfall worldwide by focusing on regional monsoon systems (Wang and Ding 2006; Zhou et al. 2008a, 2009; Zhang and Zhou 2011). Wang and Ding (2008) and Zhou et al. (2008b) explicated the basic features of the monsoon system including its causes and its relationship with atmospheric circulation and oceanic forces. Krishnamurti and Bhalme (1976) conducted a classical study of monsoon system. The authors addressed all possible elements that can affect the oscillation of monsoon system and traced a quasi-biweekly oscillation in these elements of the summer monsoon system. Webster et al. (1998) investigated the physical process of monsoon, its variability and aspects of future prediction by analyzing the coupled ocean-global atmosphere system. Fasullo and Webster (2002) developed a hydrological relationship between the Asian summer monsoon and ENSO. Further, they explored the physical entity between summer monsoon and ENSO. Saeed et al. (2011a) documented the influence of mid-latitude wave train on the surface heat low and its relationship to monsoon rainfall in the northwestern India and Pakistan. The authors confirmed a significant role of the surface heat low connecting it with the mid-latitude wave train and the Indian summer monsoon over Pakistan as well as the domain of northwestern India. Saeed et al. (2011b) examined the variability of summer monsoon rainfall over the South Asia heat low region and associated it with large scale circulation over East Asian summer monsoon rainfall through large scale teleconnection.

The mechanism of the sub-seasonal variation of the summer monsoon rainfall has been explained by numerous studies (Goswami and Goswami 1992; Goswami 1998;

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Sperber et al. 2001). Gadgil and Asha (1992) investigated inter-seasonal variation of the summer monsoon rainfall over the Indian region. The authors explored that active and break phases of the monsoon are associated with the tropical convergence zone. The tropical convergence zone remains over the continental land-mass during the active monsoon phase, in reversal, over the equatorial Indian Ocean during the break phase of monsoon. Goswami et al. (1999) studied the broad-scale circulation for the Indian summer monsoon variability and found the large seasonal shift of the tropical convergence zone.

As part of a geographically distributed global monsoon system, the South Asian summer monsoon rainfall is a significant climatic phenomenon. This climatology has an impact on the lives of people in South Asia from June to September every year. India, Pakistan, and Bangladesh are highly populated countries in this region and monsoon rains are critical to water availability and food sufficiency. Thus, the agricultural calendar set following the monsoon system of the region. Fluctuations in the South Asian summer monsoon duration, areal extent and rainfall amount often cause devastating floods and droughts.

Several studies have examined the variability of rainfall on both spatial and temporal scales in South Asia. Ichiyanagi et al. (2007) investigated the spatial and the temporal variabilities of rainfall in Nepal and found a positive relationship of the summer monsoon rainfall in western Nepal with the All Indian Rainfall and the Southern Oscillation Index. Shahid (2010) examined the rainfall variability and magnitude in Bangladesh and observed an increase in annual and pre-monsoon rainfall, while seasonal examination revealed a significant decrease in dry months during monsoon and pre-monsoon seasons. Similarly, Wickramagamage (2010) studied the seasonality and spatial patterns of rainfall in Sri Lanka and confirmed the existence of high spatial variation in rainfall on the sub-seasonal level. Hussain and Lee (2014) documented the long-term variability and changing rainfall regime in Pakistan. The study mainly focused on old and the new regime of rainfall and suggested that the latest global standard normal period of 1981–2010 is the most important for the planning of national projects. They also discovered a strong relationship between the Indian summer monsoon rainfall and rainfall patterns in the northeastern and the upper-Indus plain of Pakistan.

The summer monsoon season in South Asia characteristically starts in late May or early June (Krishnamurti and Bhalme 1976; Wang and Fan 1999; Oza and Kishtawal 2014). The rainy season of South Asia is known as the Indian summer monsoon rainfall (ISMR). The ISMR is characterized by high variability on both temporal and spatial scales (Munot and Kothawale 2000) and has been investigated by many researchers. Some notable studies of ISMR variability include Zveryaev and Aleksandrova (2004), Yadav (2009), Zhou et al. (2010), Moron and Robertson (2014), Singh et al. (2014) and Panda and Kumar (2014). The summer monsoon rainfall in Pakistan begins near the end of the ISMR. Generally, Pakistan has a more continental climate than other parts of South Asia and a diverse topology throughout the country. Therefore, Pakistan receives less rainfall, but it is also characterized by high temporal and spatial variation.

Pakistan summer monsoon rainfall (PSMR) is an extension of the ISMR. PSMR contributes the greatest amount of rainfall to the annual total in Pakistan. The PSMR is critical for agriculture, water resources, and hydro-power projects in Pakistan from June to September every year. As a major contributor to total rainfall, the PSMR system provides an enormous amount of water to the Indus water network. This is the primary water source for the irrigation system of Pakistan used for the crops of the Kharif season and imminent Rabi season. The food production is largely depends on timely rainfall, which is essential for huge population of Pakistan. Considering the present scenario, the foremost feature of this study is to investigate and analyze the variability in summer monsoon rainfall in regions of homogeneous rainfall (Hussain and Lee 2009) in Pakistan. These homogeneous rainfall regions are categorized by a particular rainfall regime. Regions 1 and 2, are mainly characterized as the regions by having the lowest amount of rainfall. Region 3 differs from region 1 because of the greater amount of winter rainfall. Region 4 represents the north western parts of Pakistan and this region receives heavy amount of rainfall during late winter and early spring. Region 5 is the wettest part of the country with heavy bulk of rainfall during early spring and the summer season. Region 6 consists of the upper-Indus plain and has main feature of heavy rainfall during summer season.

Being a vast country with a large spatial variability of monsoon rainfall, some are of Pakistan receives deficient rainfall, while some other areas face excessive rainfall. However, there are particular regional differences in the monsoon rainfall variability, which have significant consequences. In this connection, a study on monsoon rainfall on regional level becomes significant. The main objective of this study is to investigate the variability of summer monsoon rainfall in Pakistan. To this end, the paper investigates the inter-annual and intra-seasonal variabilities of the daily summer monsoon rainfall in Pakistan and the homogeneous rainfall regions of the country.

2 Data and methodology

The rainfall data analyzed in this study were provided by the Pakistan Meteorological Department (PMD). The daily rainfall data from a network of 32 weather stations was collected (Fig. 1) during the period of 1980–2014. Ever since data quality is an essential aspect of rainfall studies; thus, data reliability was sought to identify any obvious outliers in the datasets investigated. Therefore, a quality check of the data was performed by the PMD. The regional rainfall was computed by averaging all the data from stations located within a rainfall region. Further, the rainfall (in millimeters) was the total amount measured during each month of the summer rainfall season. The summer rainfall season (JJAS) was defined starting from June 1st to September 30th. All stations revealed a specific regime during the JJAS period where the majority showed peaks during August. A summary of the JJAS rainfall statistics has been mentioned in Table 1. The statistical expressions (mean, standard deviation, coefficient of variation, and Kendall tau-based correlation) were used to examine the rainfall variability. The monsoon domain can be defined by the definition provided by Zhang and Zhou (2011) and Wang and Ding (2008).

To assess the daily rainfall variability during the intra-monsoonal season of Pakistan, the daily normal rainfall (DNR) was calculated for the JJAS from June 1 to September 30 in all the rainfall regions of the study area during the period from 1980 to 2014. The daily normal rainfall of the JJAS series was divided into three periods: the pre-active period, active period, and post-active period. The average of the daily normal rainfall (ADNR) over the 122-day period was computed and used as the classification criteria for the three monsoon periods in all the homogeneous rainfall regions of Pakistan. The period from June 1 until the first day with a rainfall amount ≥ADNR was defined as the pre-active monsoon period. Similarly, from the first day with a rainfall amount ≥ADNR to the last day of rainfall ≥ADNR was considered the active period of the monsoon season. The remainder of the 122-day series was defined as the post-active period of monsoonal rainfall.

In this study, the rainfall variation was expressed by the standard deviation and by coefficient of variability (CV). The CV was calculated by dividing the standard deviation by mean average rainfall for the each region in the each period. As the excessive and deficient amounts of annual rainfall have a great impact on agriculture in Pakistan, and therefore such parameters, were identified in the investigated dataset. The averaged JJAS-rainfall anomalies exceeding ±1 standard deviation of the average rainfall are referred as excessive/deficit rainfall year, respectively. These criterion have been also used by Munot and Kothawale (2000) and Singh et al. (2014). Values of annual and seasonal rainfall were plotted in an anomalies time series. The CV of rainfall was expressed as a percentage, based on the equation:

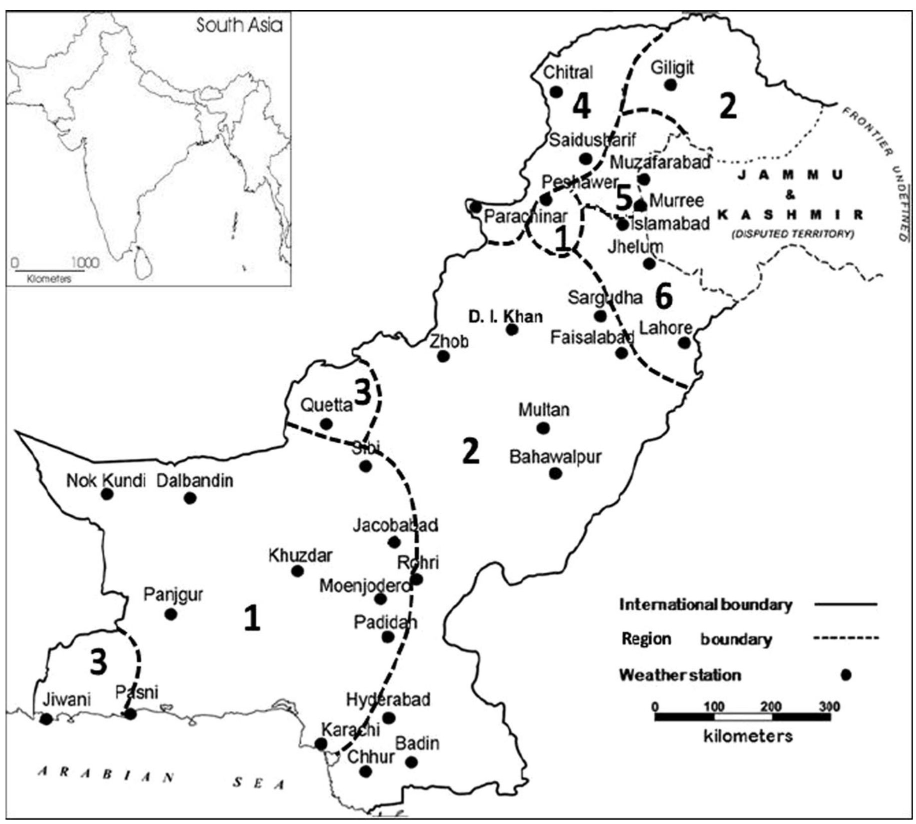

Fig. 1 Location of the 32 weather stations and identified homogeneous rainfall regions (Hussain and Lee 2009) used in this study

Table 1 General statistics of the JJAS-rainfall over homogeneous rainfall regions of Pakistan

Region	Mean (mm)	Standard deviation	Coefficient variation (%)
1	19.8	12.98	65
2	46.8	21.8	46
3	4.3	6.59	151
4	64.3	21.67	33
5	211	42.84	20
6	161	40.74	25
Pakistan	55	16.15	26

$$\mathrm{CV} = \frac{\mathrm{SD}_i}{R_i} \times 100$$

where SD is the monthly or annual standard deviation; R, monthly rainfall average; and i, the particular month of the year. The excess and deficit rainfall years were calculated by formula *a* and formula *b,* respectively:

$$a)\, R_i \geq \mathrm{R}\ + \mathrm{SD} \quad b)\, R_i \leq \mathrm{R}\ - \mathrm{SD}$$

where R_i is the rainfall of ith year, R is the mean, and SD is the standard deviation of the dataset. If the standardized rainfall is $\geq$1.0, the year is considered an excess year and if it is ≤ -1.0, the year is considered a deficit year. The relationship to regional monsoon rainfall was assessed using the Kendall *tau*-based slope estimator. The significance level of the results was tested using the classical *t* test which was determined at 95 and 99 %. To evaluate the agreement of the regional time series relationship, the regression line was fitted in a scatter plot.

3 Results

All the homogeneous rainfall regions of Pakistan have different annual and seasonal rainfall patterns. Throughout the entire study area, average rainfall remains between 5 and 300 mm. In most of the study area, July and August have demonstrated the highest rainfall. The results indicate there is a large amount of rainfall over regions 5 and 6, while at the same time region 3 is quite dry. An examination of a rainfall data-series by Hussain and Lee (2014) also concluded that the bulk of moisture is located in northeastern Pakistan (regions 5 and 6) during the summer season.

3.1 Inter-annual variability of summer monsoon rainfall

Generally, arid and semi-arid regions are characterized by high inter-annual rainfall variability. In Pakistan, all regions have a CV between 20 % (region 5) and 151 % (region 3). The northeastern regions and the country as a whole have the lowest annual variation (CV <33 %) during the JJAS. At the south-central Pakistan, the CV of rainfall is 46 %, which strongly affects most of the country.

Although the seasonal variation in rainfall is more informative, yet the annual CV is noticeably high during the investigated period. Figure 2 shows annual summer rainfall variability among the six homogeneous rainfall regions and for the entire country. The dashed horizontal lines denote the mean rainfall plus one standard deviation and the mean minus one standard deviation, and the vertical bars represent the rainfall anomalies. The years above and below the horizontal lines represents the excess and deficit rainfall years. The time series plot of JJAS rainfall precisely shows the evolution of rainfall anomalies with 5-year moving averages. This helps to identify the differences in regional averages standard departures of the JJAS rainfall.

The first 10 years in the rainfall records have a majority of negative anomalies in all regions. During the 1990s, the anomalies are positive in regions 5 and 6, but in regions 1, 2, 3, and 4, most of the anomalies are negative. However, the last few years of the dataset (2010–2013), have shown mostly positive anomalies across all rainfall regions during the JJAS season. Furthermore, for the entire country, the majority of anomalies were positive during the last decade of the studied period.

According to the investigated data, the transition of the negative and the positive anomalies were not uniform during the period from 1980 to 2014. There are no consecutive wet periods of more than 4 years in region 1 (2010–2013) and region 6 (1994–1997). Similarly, there were no consecutive dry periods of more than 7 years (1996–2002) in region 1 and more than 5 years (2001–2005) in region 5. The years 1994 and 2010 are excess rainfall years in Pakistan. The last few years (2010–2013) of the dataset are characterized as excess rainfall periods throughout Pakistan, and the decade of 1980s has the majority of deficit rainfall years. The year 2014 is a deficit rainfall year in all regions and for the entire country. The years of 1987, 2002, and 2014 have shown common droughts to all rainfall regions and the entire country during the JJAS period.

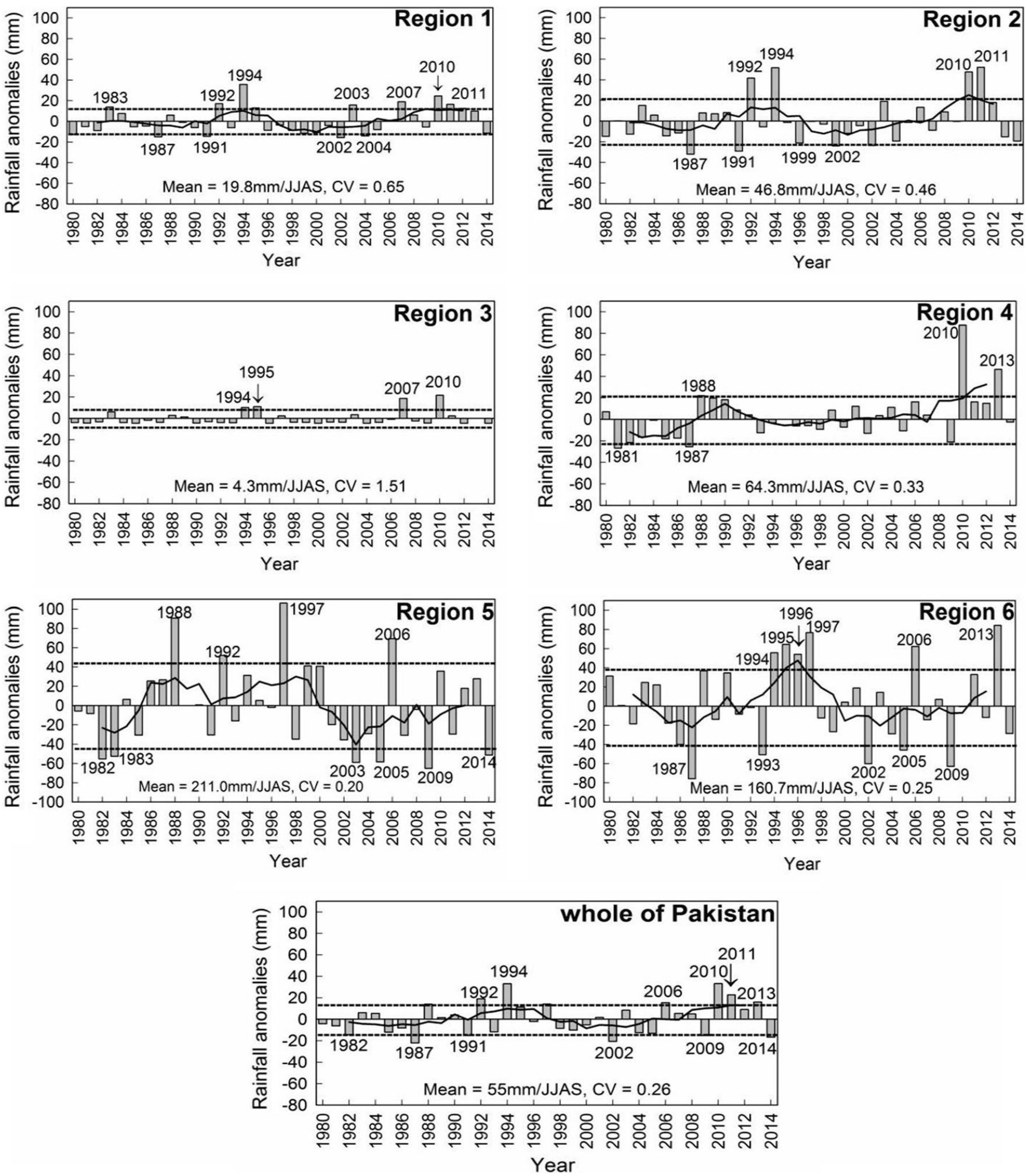

Fig. 2 Time series of JJAS rainfall (*bars*) and 5-year moving average (*lines*) with CV, from 1980 to 2014

Differences in summer monsoon rainfall characteristics exist among the rainfall regions. The JJAS rainfall of regions 1 and 2 contributes a large portion of the inter-annual variability at approximately 65 and 46 %, respectively. However, in regions 1 and 2 the JJAS rainfall contributes about 49.9 and 66.1 % to the regional JJAS season mean and 3.9 and 9.2 % to the annual mean of rainfall in Pakistan overall, respectively. In contrast, regions 5 and 6 contribute roughly 52 and 69 % to the regional JJAS season mean and 41.6 and 31.7 % to the annual mean rainfall in Pakistan. Regions 5 and 6 have inter-annual variability of 20 and 25 %, respectively, which is less than regions 1 and 2.

Examination of the correlation between the JJAS season rainfall in all regions establishes clear distinctions among the rainfall regions of Pakistan. The correlation between the daily rainfall of the JJAS season in region 1 and the JJAS rainfall in all of Pakistan is 0.677 for the period from 1980 to 2014 at a significance level of 99 %. For region 2, the correlation between the daily rainfall of the JJAS season and the JJAS rainfall of the entire country is 0.573. Similarly, the linear trend of the JJAS rainfall of regions 5 and 6 is correlated with the JJAS rainfall of Pakistan. The inter-correlation of the regional rainfall supports the hypothesis of the summer monsoon rainfall regime in the country. A scatter plot of the JJAS rainfall in the various rainfall regions compared to Pakistan as a whole during 1980–2014 is provided in Fig. 3. The correlation between the JJAS rainfall regions and the JJAS rainfall of Pakistan are positive and strong. The *r*-square values of the scatter plots range from 0.022 to 0.880. However, the *r*-square value of region 3 reveals a strong negative relationship to the summer monsoon rainfall of Pakistan. The Kendall *tau*-based slope estimator and the *r*-square value in Fig. 3 confirm the disparity between region 3 and Pakistan's overall monsoonal rainfall.

3.2 Intra-seasonal variability of summer monsoon rainfall

The summer monsoon season is highly sensitive to daily rainfall variability, and daily rainfall is highly variable both in time and in space. Intra-seasonal variability is substantial from year-to-year. The series of 122 days of the JJAS normal rainfall was divided into three periods: the pre-active period, active period and post-active period. Figure 4 shows the daily variability of the JJAS-rainfall in homogeneous rainfall regions and the entire country. The criteria for the demarcation of these three periods of summer monsoon rainfall are explained in the part of methodology. Regions 3 and 4 are excluded because of being outside the JJAS rainfall regime.

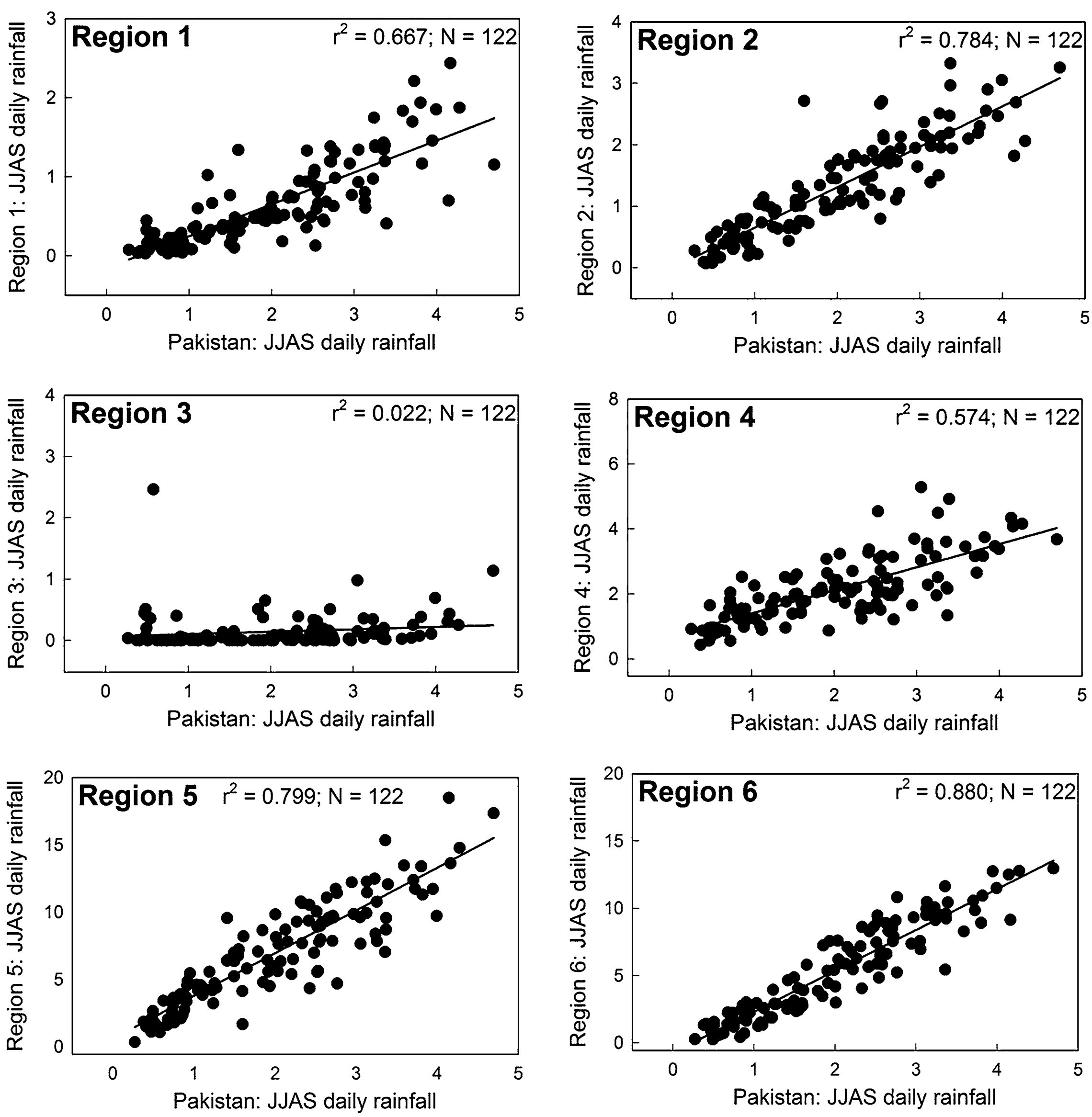

Fig. 3 Scatter plot of the standardized rainfall during the period of JJAS in homogeneous rainfall regions of Pakistan

During the pre-active period of the summer monsoon, the daily average rainfall increases in early June, then becomes slightly stable in mid-June and at the end of June starts to rapidly increase for the entire territory of Pakistan. In regions 1 and 2, a gradual increase in rainfall begins in late June and early July, respectively. A minor decrease in region 2 occurs towards the end of mid-June. In region 5, the first few days of mid-June show minor variations, whereas in region 6, the pre-active period of the summer monsoon has a steady increase.

The averages of the daily normal rainfall were also calculated for the active period. The averages of daily normal rainfall fluctuates between 0.9 mm (region 1) and 8.6 mm (region 5), and 2.7 mm for the entire country during the stage of the active period. In regions 1 and 2 during the last few days of July and the first few days of August, 1.4–1.7 mm and 2–2.5 mm rainfalls are observed, respectively. In region 2, the daily rainfall has low amplitude in late August (20–23 August for 1980–2014) during the active period. In region 5, the high peak of the summer monsoon is in mid- to late July and for region 6 late July to early August. The monsoon rainfall was active from July 3 to September 14 for region 1, June 29 to September 6 for region 2, June 24 to September 16 for region 5 and June 29 to September 6 for region 6. For the whole Pakistan monsoon rainfall is active during June 29 to September 10.

The daily rainfall in Pakistan sharply decreases during the post-active period. The amplitude of daily rainfall in the post-active period in Pakistan varies between 0.3–1.5 mm. Region 5 and 6 have 6.8 and 5.2 mm rainfall, respectively, during the post-active period. Region 5 varies slightly during the post-active period, which again shows an increase in daily rainfall values after the last day of the active period.

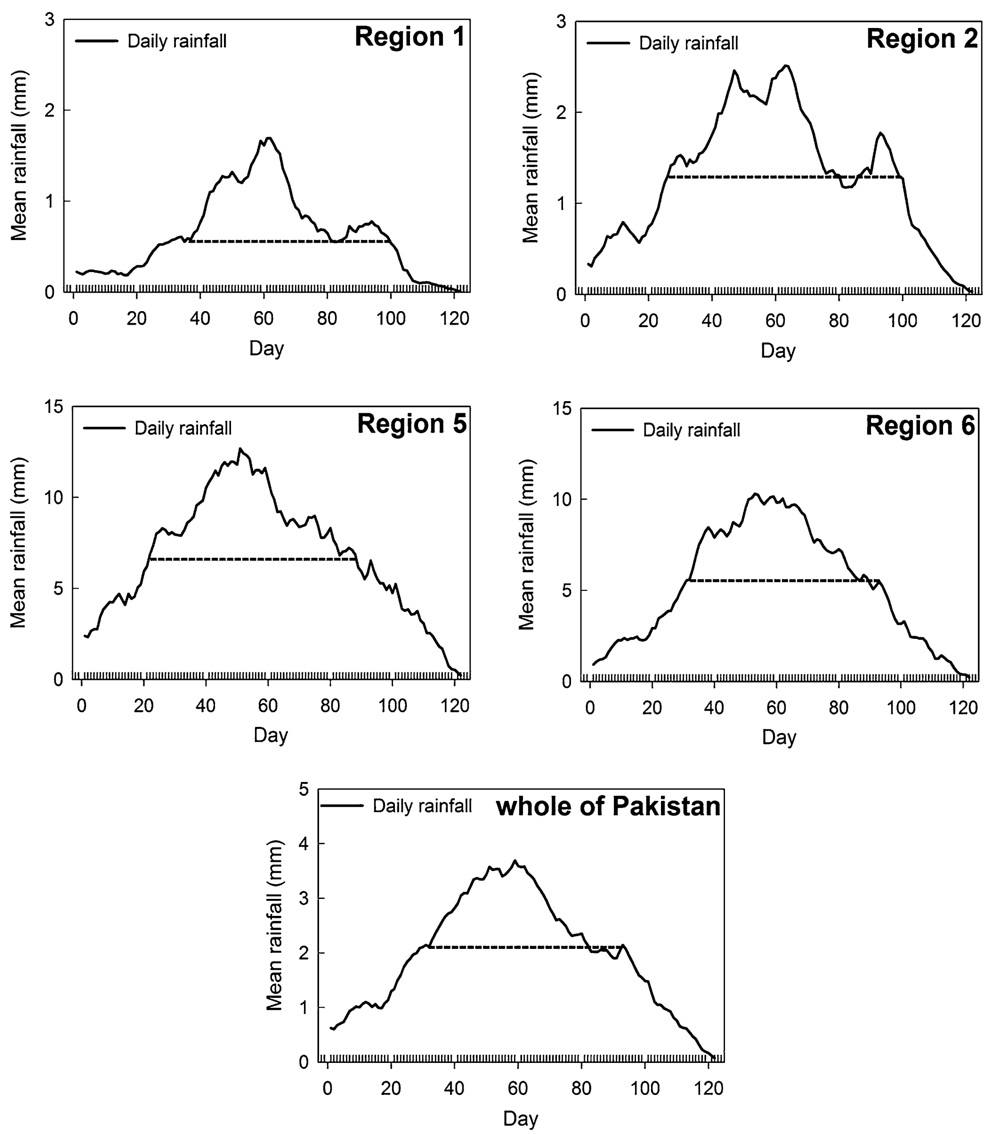

Fig. 4 Pre-active period, active period, and post-active period of rainfall in the JJAS season. *Horizontal lines* indicate the active period

Additional details of the rainfall variation and the magnitude of daily rainfall are provided in Table 2 as rainfall percentages and total number of days of pre-active, active, and post-active periods. The differences among the homogeneous regions in daily rainfall variability are clear. These values are helpful for understanding where the bulk of moisture is during the monsoon season and its variability across the country. During the pre-active period of 28 days, Pakistan receives 10.8 % of its rainfall, which varies between 0.50 and 2 mm over the entire study area. Regional rainfall fluctuates between 8 and 12 % during the pre-active period of the JJAS. The proportion of the daily rainfall of regions 2 and 5 is almost similar during the pre-active period of the JJAS season.

During the active period of the JJAS season, Pakistan receives 82.1 % of its rainfall in 74 days. Daily average rainfall is between 2 and 5 mm during this active period from 1980 to 2014. Regional rainfall varies from 67 to 88 % during the active-period of the JJAS season. The data predicts that the rainfall of region 2 and rainfall of region 6 reveal almost similar rainfall percentages share during the active period of monsoon.

The post-active period of the JJAS has more rainfall variation. This is especially apparent in region 6, where variations were between 0.24 and 5.22 mm, which constitutes 64 % of the CV. Daily rainfall frequency for entire Pakistan is between 0.4 and 1.5 mm (CV 43 %) in the post-active period of the JJAS season during the period from 1980 to 2014.

Figure 5 shows the mean number of rainfall days and mean rainfall intensity for each month of the JJAS season from 1980 to 2014. Rainfall intensity was calculated as the total yearly rainfall divided by the number of rainfall days in the year. Each region and the entire study area were examined for seasonal variability and sub-seasonal rainfall intensity. The results of rainfall intensity demonstrate the differences among the homogeneous rainfall regions. During both the JJAS season and individual months, regions 1 and 2 have the highest rainfall intensities and lowest numbers of rainfall days of the study area. However, regions 5 and 6 also have high rainfall intensity, but with high numbers of rainfall days. In June, region 2 has high rainfall intensity with the lowest number of rainfall days and region 5 has high rainfall intensity with the highest number of rainfall days. During the month of September, regions 1 and 2 have comparatively high intensities with low numbers of rainfall days and regions 5 and 6 have high rainfall intensities with a high number of rainfall days. In July and August, region 2 has the highest rainfall intensity with a low number of rainfall days. However, region 5 has low amplitudes of rainfall intensity with the highest number of rainfall days. Region 3 has low rainfall intensities compared to the rest of the entire territory.

Table 2 Percentage of rainfall of the JJAS season (a) and the number of days (b) in the period during the 122 day-series for all of Pakistan and rainfall Regions 1–6 (1980–2014)

	Pakistan	*R*1	*R*2	*R*4	*R*5	*R*6
a. Percentage						
Pre-active	10.82	10.17	9.80	12.05	9.10	8.36
Active	82.12	87.53	83.70	67.38	86.39	83.27
Post-active	7.06	2.30	6.50	20.57	4.51	8.37
b. No of days						
Pre-active	28	32	28	23	23	28
Active	74	74	74	63	85	70
Post-active	20	16	20	36	14	24

4 Discussion

This analysis of JJAS-rainfall is useful for understanding the variation in summer monsoon rainfall in Pakistan. Drought and flood, prediction requires a record of the abnormalities in rainfall for effective planning and management. Dataset duration affects the ability to identify variability in rainfall, particularly in arid and semi-arid climatic zones. Generally, long-term records are needed to investigate the trends and variation of the climatic data series. Although the data of 10 years or more are considered enough to evaluate rainfall means (Kwarteng et al. 2009), the dataset was evaluated for a period of 35 years in this study.

Rainfall variability is investigated frequently for the assessment of global climate change and adaptation strategies (Awan et al. 2014; Panda and Kumar 2014). Researchers agree that the Indian summer monsoon has a large variation and vast impact on agriculture and related aspects of the economy (Munot and Kothawale 2000; Ghosh et al. 2009; Yadav 2009). The monsoon season fluctuates temporally from the beginning of June to the end of September across South Asia. Thus, some regional differences in its onset and withdrawal can be observed (Moron and Robertson 2014; Oza and Kishtawal 2014). In South Asian countries, roughly 50 to 75 % of the annual rainfall happens in the JJAS season (Hussain and Lee 2013; Joseph et al. 2013).

According to knowledge, there has not been much work done on the rainfall variations of Pakistan. However, there are some notable studies performed on rainfall variability. Naheed and Rasul (2011) and Hussain and Lee (2014) observed variations in rainfall and found an increase in rainfall from the north to the south in Pakistan. The Intergovernmental Panel on Climate Change (IPCC 2007) also reported an increase of +40 % in rainfall over

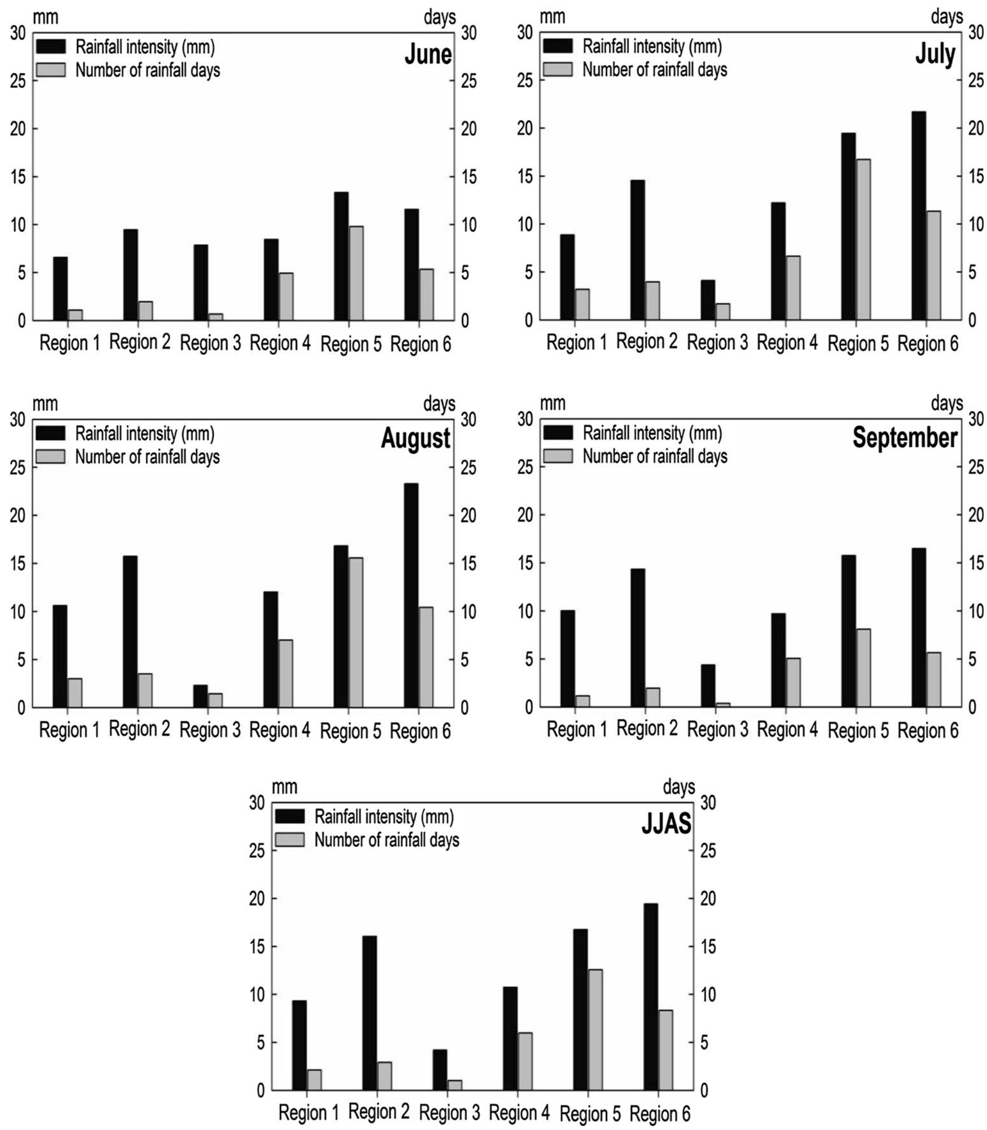

Fig. 5 Evaluation of mean intensity and mean number of rainfall days for individual months and the JJAS season in Pakistan during 1980–2014

southeastern Pakistan. Rainfall regions 2, 5, and 6 are located in the Murree hills, the Salt range, the foothills of the Himalayas, the upper-Indus plain, and the south-central Plains. The summer rainfall climatology of these areas is controlled by the monsoon system. The monsoon winds travel from the Bay of Bangla to the Assam hills, Cherrapunji and over a long distance across the great Indo-Gangetic plain, and end as they enter Pakistan. Thus, these winds do not influence northwestern Pakistan due to their weakened strength and topography hurdles such as the Murree hills, the Margala hills (Islamabad area, the capital of Pakistan), and the Pir Punjal range.

The years of 1987, 2002 and 2014 were observed as El Nino years and Pakistan receive very low rainfall during the El Nino event (Mahmood et al. 2009). Goswami 1998 confirms the deficit rainfall and ENSO cycle in 1987. The ENSO imply a weak monsoon over Pakistan and this is the immense reason for common drought years in entire the country. Interestingly, Pakistan receives more rainfall than normal in the very next year after the El Nino event during summer monsoon season. It is essential to describe how warm phase of ENSO is the cause of decreasing rainfall over Indian continent. The large-scale circulations permit the equatorial ITCZ to form more repeatedly and for lengthier period during the warm phase of ENSO. This leads to higher rainfall over ocean and subsidence over the land through the local Hadley circulation. Resulting decreased rainfall over the Indian summer monsoon rainfall region. The drought in 2002 is largely resulting deficit rainfall in the month of July. Singh et al. (2014) also confirm a deficit of July rainfall in 2002.

The magnitude of rainfall intensity in regions 1 and 2 (Fig. 5) endorses the analysis (Hussain and Lee 2013) of increasing trends of extreme rainfall over south-central

Pakistan (regions 1 and 2). This study also confirms the findings of Guhathaurta and Rajeevan (2008) and Hussain and Lee (2014) on rainfall regime in Jammu and Kashmir and the Murree hills during the months of August. The PSMR experiences significant inter-annual variability mainly in the form of excess or deficit rainfall. When rainfall is excessive or deficient on a large scale during the JJAS season, the impacts are critical to agriculture and related aspects of the economy in Pakistan. Thus, the knowledge of rainfall variability is a practical concern in relation to agriculture and water resources. Consequently, the information about these drought/flood rainfall years is enormously important.

5 Conclusion

Summer monsoon-rainfall variability was analyzed using the daily rainfall data of 32 weather stations during the period from 1980 to 2014 in Pakistan. This study explored the inter-annual and the intra seasonal daily rainfall variability of the PSMR. Evaluation of the inter-annual variability was conducted using the CV and the intra-seasonal variability measured by calculating the daily normal rainfall of the JJAS season. A multivariate correlation was calculated to understand the relationships between rainfall seasonal climatology of homogeneous rainfall regions and the pattern of the JJAS-rainfall in Pakistan.

The variability of the inter-annual rainfall of the summer monsoon ranged from 20 % in the northwestern parts to 65 % in the southwestern parts of Pakistan. The transition of excessive and deficient rainfall years was not uniform in the data of the JJAS rainfall investigated. The years 1994 and 2010 were excessive rainfall years and the years 1987 and 2002 had the foremost drought in Pakistan. In the decade of 1990, the inter-annual variability noticeable by predominance of the positive anomalies for the Murree hills and the Salt range, whereas in the upper-Indus plain, the south-central-plain and the western-southern Pakistan is marked by most of anomalies as negative. However, for the entire country, majority of anomalies were frequently positive during the last decade of the period studies.

The correlation of regional rainfall of the JJAS season establishes clear distinctions among the rainfall regions of Pakistan. The association of the regional JJAS rainfall and the JJAS rainfall of Pakistan are positive and strong. However, region 3 exhibits a strong negative relationship to the summer monsoon rainfall. Evaluation of the interrelationships of the regional rainfalls confirmed that the western parts of the country are located far from monsoonal access.

Analysis of the intra-seasonal rainfall reveals the pre-active period is not a significant contributor to the intra-monsoonal rainfall from 1980 to 2014. Regional rainfall fluctuates from 8 to 12 % and its amplitude is between 0.5 to 8.2 mm during the pre-active period of the summer monsoon season. The JJAS rainfall is vigorous for 74 days (June 29 to September 10) and received 82.1 % of the rainfall during the active period of JJAS for the entire territory of Pakistan. In homogeneous regions, summer monsoon rainfall is active for 70–85 days and its range is 67–88 % for region 1 (July 3 to September 14), region 2 (June 29 to September 6), region 5 (June 24 to September 16) and region 6 (June 29 to September 6) during the active period. The magnitude of daily normal rainfall fluctuates between 0.7 mm (region 1) and 6.9 mm (region 5), and about 2 mm for the entire country during the stage of the active period. Daily rainfall frequency for entire Pakistan is between 0.4 and 1.5 mm (CV 43 %) in the post-active period of the JJAS season. A detailed analysis of this data has showed the noteworthy contribution of the rainfall of late July and early August to the total rainfall in the JJAS season.

From the analysis of the available data, it can be concluded that the inter-annual variation of rainfall, which has high variability in the southwestern parts of the country. Inclusively, three prominent features of the summer monsoon rainfall can be marked in Pakistan: (1) correlation analysis coincides with the established JJAS rainfall regime in the country; (2) the intra-seasonal variability is significantly different during June and September; (3) it is evident that August is typically a month with heavy rainfall where the pattern of summer monsoon rainfall changes.

Knowledge of the JJAS rainfall can provides a large-scale estimate of rain requirements for farmers during the summer season. Experimental approaches to the elucidation of variability in the JJAS rainfall are also important and useful for policy requirements related to urban drainage systems, water resource management, and power generation projects in the country. An important implication of this study is that the causes prevailing variability of the summer monsoon are likely dissimilar to the individual months of the JJAS season. Information of sub-seasonal rainfall is essential for the perfect forecast of droughts and floods. Therefore, further study is required to analyze the variability of sub-seasonal rainfall during the summer monsoon season, which can provide the vibrant information for the people of Pakistan.

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