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Variability, trends, and teleconnections of observed precipitation over Pakistan

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Abstract The precipitation variability, trends, and teleconnections are studied over six administrative regions of Pakistan (Gilgit-Baltistan or GB, Azad Jammu and Kashmir or AJK, Khyber Pakhtoonkhawa or KPK, Punjab, Sindh, and Balochistan) on multiple timescales for the period of recent 38 years (1976–2013) using precipitation data of 42 stations and circulation indices datasets (Indian Ocean Dipole [IOD], North Atlantic Oscillation [NAO], Arctic Oscillation [AO], El Niño Southern Oscillation [ENSO], Pacific Decadal Oscillation [PDO], Atlantic Multidecadal Oscillation [AMO], and Quasi-Biennial Oscillation [QBO]). The summer monsoon season received the highest precipitation, amounting to 45%, whereas the winter and pre-monsoon (post-monsoon) seasons contributed 30 and 20% (5%), respectively, of the annual total precipitation. Positive percentile changes were observed in GB, KPK, Punjab, and Balochistan regions during pre-monsoon season and in Balochistan region during post-monsoon season in second half as compared to first half of 38-year period. The Mann-Kendall test revealed increasing trends for the period of 1995–2013 as compared to period of 1976–1994 for entire Pakistan during monsoon season and on annual timescale. A significant influence of ENSO was observed in all the four seasons in Balochistan, KPK, Punjab, and AJK regions during monsoon and post-monsoon seasons. This study not only offers an understanding of precipitation variability linkages with large-scale circulations and trends, but also it contributes as a resource document for policy makers to take measures for adaptation and mitigation of climate change and its impacts with special focus on precipitation over different administrative regions of Pakistan.

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1 Introduction

Precipitation variability plays a significant role for agriculture production, food security, ecosystems, climate change studies, and hydrological modeling (see for instance, Ebert et al. 2007; Gordon et al. 2010, and references cited therein). Changes in precipitation patterns, shifts, and trends affect the water balance, disaster management sector, and ecosystems (Bastiaanssen and Ali 2003). Global climate risk index ranked Pakistan as the eighth most vulnerable nation in 2011 and third most vulnerable nation in 2012 among 180 countries of the world most affected by the impact of weather-related losses (Kreft and Eckstein 2013).

One of the key impacts of global climate change is an increase in the frequency and intensity of extreme precipitation events in Asia (Sheikh et al. 2015; Bharti 2016). Accurate information regarding the intensity of extreme precipitation events as pertinent to floods, droughts, landslides, coastal storms, and hill torrents are crucial for the planning, adaptation, and mitigation strategies of natural disasters (Maida and Ghulam 2011; Salma et al. 2012). Extreme precipitation events resulted in heavy floods in Pakistan, India, and China during 2010, 2011, and 2012 (Wang et al. 2011; Webster et al. 2011; Viterbo et al. 2016).

Analyzing the past trends, monitoring the changes and assessing the variability in a precipitation time series is crucial for predicting potential impacts of future climate changes over a region (Abbas et al. 2014; Ahmad et al. 2015; Dahri et al. 2016). A mixture of increasing and decreasing precipitation trends were observed in countries like Bangladesh (Shahid 2009, 2011), China (Zhang et al. 2015; Li et al. 2016), Georgia (Keggenhoff et al. 2014), India (Narayanan et al. 2013;

Pingale et al. 2014; Sharma et al. 2016), Serbia (Gocic and Trajkovic 2013), and Zimbabwe (Mazvimavi 2010). An overall increase in average annual precipitation has been observed across the globe from 1900 to 2008. The increasing (decreasing) precipitation was observed in Northern Europe, Central Asia, and eastern parts of North and South American (Southern Africa and parts of Southern Asia) regions (IPCC 2013).

Generally, parametric and non-parametric statistical techniques are used for analyzing the variability and trends in precipitation time series (Voss et al. 2002; Zolina et al. 2009; Schär et al. 2016). Parametric tests, including linear regression analysis, are considered more powerful tests as compared to non-parametric ones, however, require independent and normally distributed data which is rarely available for hydrometeorological variables (Pingale et al. 2014). Therefore, non-parametric tests are commonly used for regional and global level. Most frequently and commonly used non-parametric test is Mann-Kendall (MK) (Kendall 1938; Mann 1945), along with Sen's slope estimator (SSE) (Sen 1968). In recent past, precipitation time series has been studied using these non-parametric tests for analyzing the trends and magnitude of change (see for instance, Khattak et al. 2011; Hanif et al. 2013; Hussain and Lee 2013, 2014).

The diverse causes of climate variations include moisture transportation, atmospheric circulations, fluxes of heat, and large-scale ocean circulations. Among these causes, large-scale ocean circulations occur in recognizable variability patterns through teleconnections (Wallace and Gutzler 1981). The teleconnections mimic the atmospheric and oceanic patterns of the earth's climate (Thompson and Rahmstorf 2009; Saeed et al. 2011). The identification of teleconnections pattern occurrence in terms of circulation indices and their evolution provides a better understanding of climate change (Syed et al. 2012; Krichak et al. 2014). This identification is most commonly applied to assess the climate variability on monthly and longer timescales. Commonly used circulation indices linked with precipitation variations include Indian Ocean Dipole (IOD), North Atlantic Oscillation (NAO), Arctic Oscillation (AO), El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), and Quasi-Biennial Oscillation (QBO), and other teleconnections (See for instance, Syed et al. 2010; Wu 2013; Athar 2015; Liu et al. 2015; Krishnamurthy and Krishnamurthy 2016; Seidel et al. 2016). Several studies have linked the influence of large-scale ocean and atmospheric circulation indices with precipitation in South Asia; however, very limited studies have been carried out over Pakistan to evaluate the impact of circulation indices on precipitation (Syed et al. 2006, 2010; Liess and Geller 2012; Krishnamurthy and Krishnamurthy 2016).

Some studies have been conducted in Pakistan for analyzing the precipitation variability and trends. For instance, Maida and Ghulam (2011) studied the frequency of extreme precipitation (and temperature) occurrence over 41 stations using non-parametric Kolmogorov-Smirnov test. An apparent increase in frequency of extreme precipitation events across the country was noticed. Salma et al. (2012) investigated the precipitation trends of 30 years in different climatic zones using analysis of variance and the Dunnett T3 test. Results of this study showed decreasing precipitation trends (− 1.18 mm/decade) over the entire country. Ahmad et al. (2015) studied precipitation trends in Swat river basin using MK and Spearman's rho test for 15 stations. The results showed a mixture of increasing and decreasing precipitation trends. Hanif et al. (2013) studied the latitudinal precipitation trends using MK test on annual and monsoon season timescales. Results revealed increasing precipitation trends in high latitudes, whereas no significant trends were observed in lower latitudes. Hussain and Lee (2013) investigated seasonal variability of extreme precipitation trends using simple linear regression and MK test for 15 stations. Increasing (decreasing) seasonal trends in extreme precipitation were observed in northeastern (southwestern) Pakistan. Abbas et al. (2014) studied the changes in precipitation extremes over Punjab region using MK test for five stations and found no significant trends.

The purpose of current study is to analyze the precipitation variability using percentiles from extremely dry to extremely heavy events and to investigate the precipitation trends using MK test along with SSE for evaluating the magnitude change. The data of 42 stations is used for the period of recent 38 years (1976–2013) over diverse and complex topography of Pakistan. Furthermore, the influence of large-scale ocean and atmospheric circulation indices (IOD, NAO, AO, ENSO, PDO, AMO, and QBO) on precipitation is also studied. The analyses are performed on multiple timescales over the six administrative regions of Pakistan including four provinces (Khyber Pakhtoonkhawa (KPK), Punjab, Balochistan, and Sindh) and two autonomous territories (Gilgit-Baltistan (GB), and Azad Jammu and Kashmir (AJK)), for the first time.

2 Study area

Pakistan is geographically located approximately between 24–37° N and 62–75° E in the western part of South Asia (Fig. 1). Pakistan has diverse elevation ranges of up to 8600 m above mean sea level in Himalayas and Karakoram range in the north and in Hindu Kush range in the north and northwest, including the Koh-e-Sulaiman Mountain range in northern part of Balochistan Province (Butt and Iqbal 2009). Pakistan has an agricultural-based economy and more than 70% of its people are engaged in agricultural activities (Bastiaanssen and Ali 2003).

The federal government allocates annual budget based on administrative regions in Pakistan (http://www.pakistan.

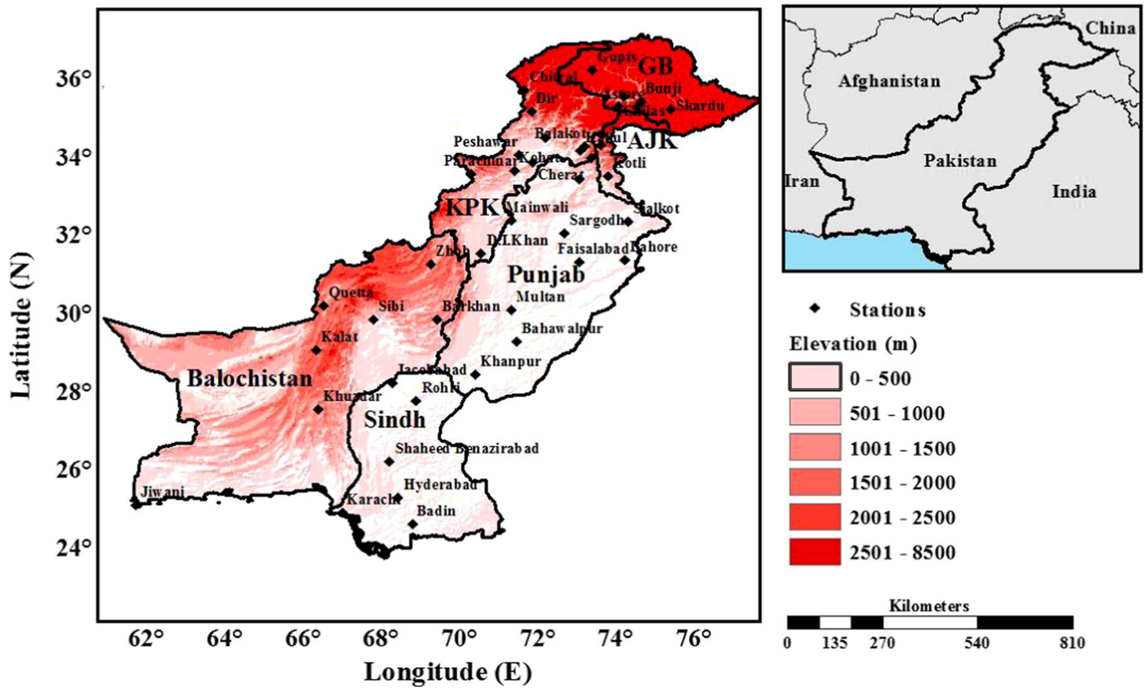


Fig. 1 Study area map along with the locations of precipitation measuring stations. See Table 1 for more details of stations

gov.pk). It is therefore significant to provide the policy makers the first estimates of the climatology of precipitation based on these six administrative regions. The administrative regions of Pakistan consist of four provinces (KPK, Punjab, Balochistan, and Sindh), Federal Capital Territory (Islamabad), two autonomous territories (GB and AJK), and a group of Federally Administrated Tribal Areas (FATA).

Two core precipitation seasons are observed in the study area including summer monsoon season (July to September) and winter precipitation season (December to March) (see for instance, Hussain and Lee 2009). The monsoon system is the core precipitation producing system of the South Asia. Monsoon system enters in Pakistan via the south westerly winds originating from coastal areas of Arabian Sea and Bay of Bengal (Hussain et al. 2010; Wang et al. 2011; Latif and Syed 2015; Hussain and Lee 2016). On the other hand, winter precipitation is dominantly associated with eastward propagating western disturbances (WDs) originating from Mediterranean and Atlantic Ocean, and then traveling eastwards over Iran and Afghanistan to reach Pakistan (Syed et al. 2010; Cannon et al. 2015; Dimri et al. 2015; Cannon et al. 2016a, b). Summer monsoon season contributes 57%, winter season contributes 30%, and remaining 13% precipitation is received during pre- and post-monsoon seasons including tropical cyclones (Wang 2006; Hussain and Lee 2009; Saeed et al. 2011; Asmat and Athar 2017). Precipitation in the study area is both latitude and elevation dependent because in north and northeast (south) 1500 to 2000 mm (100 to 200 mm) is observed for the total annual precipitation (Hanif et al. 2013).

3 Data and methodology

3.1 Data

In the current study, daily precipitation data (in units of mm/day) was acquired from Pakistan Meteorological Department (PMD) over complex and diverse topography of Pakistan. There are only 97 total stations installed by PMD across the country and approximately half of the stations were installed in the recent past (http://www.pmd.gov.pk). The spatial distribution of stations is non-uniform. Our analyses are completely based on the available station data of PMD, because station data is considered as reliable and an accurate source of information if compared with interpolated and reanalysis data. In the first step, precipitation time series with high missing values within the analysis period have been omitted. Outliers in the time series have been identified and temporal consistency was also verified, following Athar (2014). After the quality control check, the data of 42 stations are carefully selected based on three parameters including (i) the availability of long-term data, (ii) good quality data, and (iii) reliable data. The station data acquired for this study varies in different administrative regions with highest number of 10 stations each in KPK and Punjab Provinces, seven stations in Balochistan Province, and six stations each in GB and Sindh Provinces, whereas data of only three stations were used for AJK region due to fewer number of stations and small covered area. Daily dataset is converted into monthly, seasonal, and annual timescales. The seasons are divided based on precipitation patterns in the study area including winter (December to March), pre-monsoon (April to June), monsoon (July to

September), and post-monsoon (October and November) seasons. Figure 1 displays the spatial distribution of the selected stations in the study area, whereas Table 1 displays the geographic distribution of the stations and summery of the key statistics of the dataset. It can be observed that mean annual precipitation varies between 110.58 mm/year (minimum) for Jiwani and 1770.03 mm/year (maximum) for Murree. In general, stations located in the northern parts receive more precipitation compared to stations located in the southern parts of the country.

Additionally, monthly National Centers for Environmental Predication/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data with spatial resolution of 2.5° × 2.5° is utilized for plotting characteristics of regional 200 hPa zonal wind for the period of 1976–2013 (Kalnay et al. 1996; Kistler et al. 2001). The covariability of large-scale ocean and atmosphere circulation indices including IOD, NAO, AO, ENSO, PDO, AMO, and QBO and precipitation is studied for all six administrative regions at monthly, seasonal, and annual timescales for the entire period of study. These circulation indices are based on sea surface temperature (SST), sea level pressure (SLP), and equatorial zonal wind (EZW), and were obtained from various organization's websites including Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Earth System Research Laboratory (ESRL), and NCEP of National Oceanic and Atmospheric Administration (NOAA), USA, as listed in Table 2. The data of monthly circulation indices were averaged to obtain the values of four seasons (winter, pre-monsoon, monsoon, and post-monsoon) and for annual timescale.

3.2 Methodology

3.2.1 Percentile analysis

The percentiles are used to assess the variability from extremely dry to extremely heavy precipitation events. In the current study, all percentiles of both wet and dry precipitation events are utilized. The variability and changes in precipitation pattern associated with each percentile are referred to as changes in the intensity of precipitation (Schär et al. 2016). The thresholds are defined for precipitation events analysis based on percentile changes and computed from 1st to 99th at daily, monthly, seasonal, and annual timescales. The percentile threshold ranges are adopted from Doyle et al. (2012) who studied precipitation changes in La Plata Basin in southern hemisphere, with similar climatic attributes as in Pakistan. Five different threshold ranges are considered: below 10th percentile (extremely dry), between 10th–35th percentile (dry), above 35th–65th percentile (normal), between 65th–90th percentile (above normal), and above 90th percentile (extremely heavy precipitation). The nth percentiles (i.e., 1st to 99th) were computed using long-term precipitation time series for the period of 38 years for 42 stations across the country. The time series is divided into two equal halves of 19 years (1976–1994 and 1995–2013) for analyzing the percentile variability in precipitation events. For nth percentile of the data, rank r is computed using Eq. (1).

$$r = \frac{n}{100}(N-1) + 1 \tag{1}$$

where N is number records (X1, …, Xn).

3.2.2 Mann-Kendall trend test

In the current study, frequently applied non-parametric MK statistical test is used for detecting the precipitation trends. The MK test has also been suggested by World Meteorological Organization to detect the trends in hydrometeorological datasets (Ahmad et al. 2015). The MK test is essential because it does not require any assumption for the statistical distribution of the data and can be applied to the datasets with missing and irregular sampling intervals.

In MK test, H_0 (H_1) states no trend (existence of trend) in a time series. The MK correlation coefficient (Kendall's Tau) establishes the trend in a time series and the strength of the trend is proportional to the magnitude of MK test statistic, where greater (smaller) magnitude indicates stronger (weaker) trends.

First step in MK test is to determine the sign of the difference between consecutive sample results as computed in Eq. (2).

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \mathrm{sign}\left(x_j - x_i\right) \tag{2}$$

where N is the number of data points, x_i and x_j are the data values in time series i and j ($j > i$), respectively, and sign($x_j - x_i$) is the sign function and is computed using Eq. (3).

$$\mathrm{sign}\left(x_j - x_i\right) = \begin{cases} +1, & \mathit{if}\ x_j - x_i > 0 \\ 0, & \mathit{if}\ x_j - x_i = 0 \\ -1, & \mathit{if}\ x_j - x_i < 0 \end{cases} \tag{3}$$

The variance is computed using Eq. (4).

$$V(S) = \frac{N(N-1)(2N+5) - \sum_{i=1}^{m}(t_i - 1)(2t_i + 5)}{18} \tag{4}$$

where m is the number of tied groups and t_i denotes the number of ties present with sample i as extent. A tied group is a set of sample data having the same value.

Next, the standardized MK test statistics (Z_{mk}) is computed using Eq. (5).

$$Z_{mk} = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & \mathit{if}\ S > 0 \\ 0 & \mathit{if}\ S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & \mathit{if}\ S < 0 \end{cases} \tag{5}$$

Table 1 The description of station locations in administrative regions used in the study along with latitude, longitude, elevation in meters, and mean annual precipitation in millimeter. In each administrative region, stations are listed from north to south

Administrative region	Station name	Latitude (°N)	Longitude (°E)	Elevation (m)	Mean annual precipitation (mm)
GB	Gupis	36.17	73.40	2155	221.45
	Gilgit	35.92	74.33	1460	122.84
	Bunji	35.67	74.63	1372	162.77
	Chilas	35.42	74.10	1250	176.78
	Astore	35.35	74.86	2167	459.90
	Skardu	35.30	75.68	2209	230.18
AJK	Garhi Dupatta	34.22	73.62	814	1318.46
	Muzaffarabad	34.37	73.48	701	1510.86
	Kotli	33.52	73.90	613	1200.06
KPK	Dir	35.20	71.85	1369	1408.15
	Chitral	35.83	71.78	1500	450.13
	Saidu Sharif	34.73	72.35	961	1048.42
	Balakot	34.38	73.35	980	1598.57
	Kakul	34.18	73.25	1308	1319.62
	Peshawar	34.02	71.58	359	488.24
	Parachinar	33.87	70.07	1725	895.01
	Cherat	33.82	71.88	1301	568.50
	Kohat	33.57	71.43	600	565.16
	D.I.Khan	31.82	70.92	173	316.51
Punjab	Murree	33.92	73.38	2167	1770.03
	Islamabad	33.70	73.08	507	1241.13
	Mainwali	32.55	71.55	450	580.88
	Sialkot	32.50	74.53	251	980.52
	Sargodha	32.05	72.67	205	481.91
	Lahore	31.50	74.40	215	689.78
	Faisalabad	31.43	73.10	183	397.85
	Multan	30.19	71.46	122	212.61
	Bahawalpur	29.40	71.78	116	177.12
	Khanpur	28.65	70.68	87	125.30
Sindh	Jacobabad	28.27	68.45	55	149.12
	Rohri	27.69	68.85	66	114.84
	Shaheed Benazirabad	26.15	68.22	37	163.23
	Hyderabad	25.38	68.36	40	176.03
	Karachi	24.89	67.05	21	205.49
	Badin	24.16	68.57	10	244.46
Balochistan	Zhob	31.35	69.47	1405	277.99
	Quetta	30.25	66.88	1600	272.28
	Barkhan	29.88	69.72	1097	402.11
	Sibi	29.55	67.88	133	177.57
	Kalat	29.03	66.58	2015	214.88
	Khuzdar	27.83	66.63	1231	266.94
	Jiwani	25.04	61.74	56	110.58
Country normal					559.39

The Z_{mk} follows the standard normal distribution with a mean of zero and variance of one. A positive (negative) value of Z_{mk} indicates upward (downward) trend. A significant value α is utilized for testing either an upward or downward trend in two-sided test. If the Z_{mk} value is greater than $Z_{\alpha/2}$, then null hypothesis (H_0) is rejected at α level of significance.

Table 2 Details of the circulation indices used in this study. For ENSO index, the Niño 3.4 data was acquired, whereas for QBO index, data at both 30 and 50 hPa were used. The variables of the circulation indices are sea surface temperature (SST), sea level pressure (SLP), and equatorial zonal wind (EZW)

Index	Period (years)	Positive/negative years	Variability location	Variable	Website
IOD	1976–2012 (37)	1982, 1987, 1991, 1994, 1997, 2007, 2011, 2012/1978, 1980, 1985, 1989, 1992, 1996	Southeastern equatorial Indian Ocean (50°–70° E and 10° S–10° N, and 90°–110° E and 10° S–0° N)	SST	www.jamstec.go.jp/frcgc/research/d1/iod/e/iod/dipole_mode_index.html
NAO	1976–2013 (38)	1982, 1990, 1992, 2011/1996, 2008, 2010, 2012	30° N (the Azores) and low-pressure areas at 60° S (Iceland)	SLP	www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/NAO/
AO	1976–2013 (38)	1989, 1990, 1992, 1994, 2011/1977, 1980, 1981, 1985, 1987, 1996, 2010	Poleward of 20° N	SLP	www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/AO/
ENSO	1976–2013 (38)	1982, 1987, 1991, 1992, 1997/1984, 1985, 1988, 1989, 1999, 2000, 2008, 2011	5° N–5° S and 120°–170° W	SST	www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/
PDO	1976–2013 (38)	1981, 1983, 1984, 1986, 1987, 1992, 1993, 1997, 2003/1999, 2008, 2011, 2012	Pacific Ocean, north of 20° N	SST	www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/PDO/
AMO	1979–2013 (36)	1998, 2003, 2004, 2005, 2006, 2010, 2012/1976, 1982, 1984, 1985, 1986, 1992, 1993	North Atlantic over 0°–80° N	SST	www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/AMO/
QBO	1979–2013 (36)	QBO 30 (1985, 1990, 1995, 1997, 1999, 2002, 2004, 2008, 2013/1979, 1984, 1994, 1996, 2001, 2003, 2005, 2007, 2012) QBO 50 (1983, 1988, 1993, 1995, 1999, 2002, 2009, 2011/1982, 1984, 1992, 1994, 1996, 1998, 2001, 2012)	Singapore	EZW	www.cpc.ncep.noaa.gov/data/indices/

The significance value (p value) for each trend can be computed using Eq. (6) (Coulibaly and Shi 2005).

$$p = 0.5 - \varphi(|Z_{mk}|) \tag{6}$$

where $\varphi()$ denotes the cumulative distribution function of a standard normal variate.

3.2.3 Sen's slope estimator

The magnitude of the trends is computed using the Theil and Sen's median slope estimator (Theil 1950; Sen 1968). This technique gives better estimate of trends because it is not influenced by outliers. The slope is estimated using Eq. (7) for N pairs of data.

$$Q_i = median\left(\frac{x_j - x_k}{j - k}\right) \; for \; \mathrm{i} = 1, \ldots, \mathrm{n} \tag{7}$$

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

The median of the N values of Q_i is SSE of slope. If N is odd, the SSE is computed using Eq. (8), and if N is even, the SSE is computed using Eq. (9).

$$Q_{\mathrm{med}} = \frac{Q_{(N+1)}}{2} \tag{8}$$

$$Q_{\mathrm{med}} = \left[\frac{\frac{Q_N}{2} + \frac{Q_{(N+2)}}{2}}{2}\right] \tag{9}$$

Finally, Q_{med} is tested by two-sided test at 100(1-α) % confidence level (CL), and the true slope is obtained by a non-parametric test.

3.2.4 Teleconnections

The influence of large-scale ocean and atmospheric circulation indices (IOD, NAO, AO, ENSO, PDO, AMO, and QBO) is studied on precipitation occurrence over six administrative regions at monthly, seasonal, and annual timescales. The IOD is normally characterized by anomalous cooling of SSTs in the southeastern equatorial Indian Ocean and the anomalous warming of SSTs in western equatorial Indian Ocean (see Table 2 also). A positive (negative) IOD event results in surplus precipitation (droughts) (Athar 2015; Hussain et al. 2016). The NAO is the normalized SLP between the subtropical high at the Azores and low at the Iceland. The positive (negative) phase of NAO indicates a stronger (weaker) than usual subtropical high-pressure center (Syed et al. 2010; Athar 2015; Liu et al. 2015). The AO is characterized by winds circulating counterclockwise around the Arctic. When the AO is in its positive (negative) phase, a ring of strong winds circulating (winds become weaker) around the North Pole act to confine colder air across polar regions (Carvalho et al. 2005; Cannon et al. 2015).

The ENSO is composed of an oceanic component El Niño (La Niña) which is characterized by warming (cooling) of surface water in the tropical eastern Pacific Ocean, and an atmospheric component by the southern oscillation which is characterized by changes in SLP in the tropical western Pacific. The El Niño and La Niña are important quasi-periodic temperature fluctuations in the surface water of tropical eastern Pacific Ocean (Meyers et al. 2007). When the warm (cold) oceanic phase is in effect, the SLP in the western Pacific is high (low) (Syed et al. 2010; Athar 2015; Cannon et al. 2015).

The PDO is a prolonged El Niño-like pattern of climate variability in the Pacific Ocean and has been observed during the twentieth century. During a warm (cool) or positive (negative) phase, the western Pacific cools (warms) and part of eastern ocean warms (cools) (Wu 2013). The AMO is defined as the de-trended low-pass-filtered annual mean SST anomalies averaged over the north Atlantic basin (Krishnamurthy and Krishnamurthy 2016). The QBO is the mean zonal wind of the tropical stratosphere at 30–50 hPa pressure range (Liess and Geller 2012). A year is considered as positive (negative) phase when the index value falls above (below) than one standard deviation from the average for 1976–2013 (Carvalho et al. 2005; Meyers et al. 2007; Syed et al. 2010; Wu 2013; Hussain and Lee 2016).

The Pearson correlation coefficient (CC) using Eq. (10) is used to assess the magnitude of linear relationship between a circulation index and precipitation. The teleconnections analyses are performed on circulation indices data using entire time series and with both the positive and negative years separately (where applicable) to analyze the relationship.

$$CC = \frac{\sum_{i=1}^{n}\left(P_{gauge(i)} - \bar{P}_{gauge}\right)\left(Q_{index(i)} - \bar{Q}_{index}\right)}{\sqrt{\sum_{i=1}^{n}\left(P_{gauge(i)} - \bar{P}_{gauge}\right)^2} \times \sqrt{\sum_{i=1}^{n}\left(Q_{index(i)} - \bar{Q}_{index}\right)^2}} \quad (10)$$

where n is the number of observations in the time series, P (Q) is precipitation (circulation index) value, and $\bar{P}$ ($\bar{Q}$) is the mean precipitation (circulation index) value, and the range of CC is such that $-1 < CC < +1$ (see for instance, Murphy 1995; Wilks 2011). For CC analysis, the following four CC ranges are considered: weak (CC < 0.25), low ($0.25 \leq CC < 0.50$), moderate ($0.50 \leq CC \leq 0.75$), and strong (CC > 0.75). The computed CCs were tested for statistical significance using the two-tailed Student t test via Eq. (11).

$$t_{n-2} = CC\sqrt{\frac{n-2}{1-CC^2}} \quad (11)$$

where t is the value of the Student t test. For CL, the following four threshold ranges are considered: marginal CL (CL < 80%), moderate CL ($80\% \leq CL < 90\%$), strong CL ($90\% \leq CL < 95\%$), and very strong CL ($CL \geq 95\%$).

4 Results

4.1 Spatiotemporal distribution of precipitation

Figure 2 displays an overview of the spatiotemporal distribution of precipitation for six administrative regions separately for the period of 1976–1994 and 1995–2013. Increasing (decreasing) precipitation was observed in GB (Balochistan and AJK) region(s) in the later half (1995–2013) on monthly timescale. On seasonal timescale, increasing precipitation was observed in KPK region during winter season, in GB and Sindh regions during pre-monsoon, and in GB (KPK) region

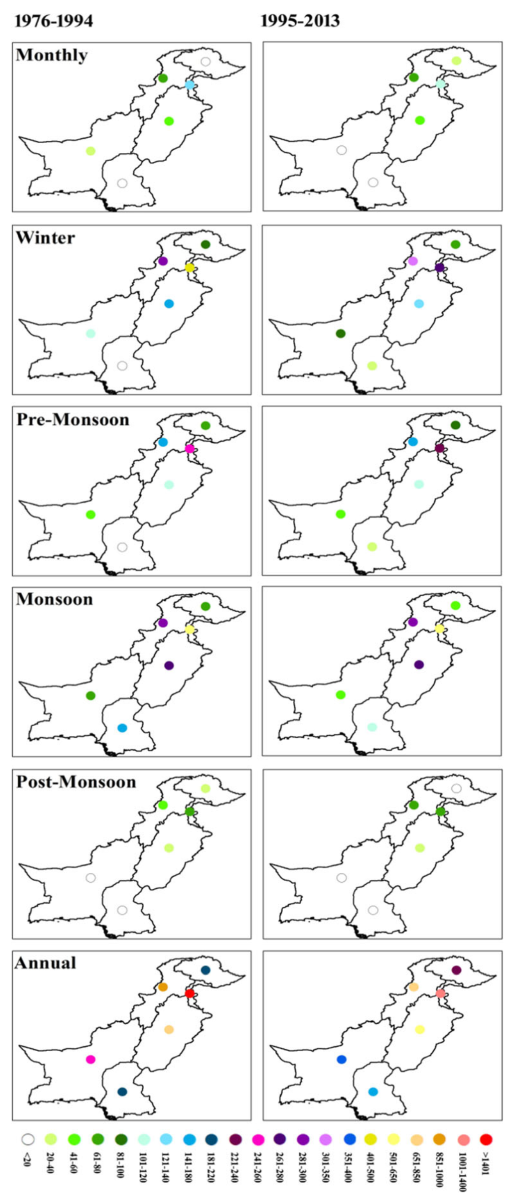


Fig. 2 Monthly, seasonal (winter, pre-monsoon, monsoon, and post-monsoon), and annual timescale precipitation (mm) variability, row wise, over different administrative regions for the two half time periods (1976–1994 and 1995–2013), in left and right column panels, respectively

during monsoon (post-monsoon) season. On annual timescale, increasing precipitation behavior was noticed in GB and AJK regions in the later half (1995–2013).

There are substantial spatial variations in precipitation across all the six administrative regions (not shown). Table 3 shows the monthly area average highest to lowest precipitation in AJK, KPK, Punjab, Balochistan, GB, and Sindh regions, respectively. Seasonally, the six administrative regions exhibited a similar pattern of precipitation distribution with highest (lowest) share during summer monsoon (post-monsoon) season. Dominant occurrence of precipitation was noticed in AJK, KPK, and Punjab regions during the four seasons. Similar behavior was also observed on the annual area average precipitation from highest to the lowest in AJK, KPK, Punjab, Balochistan, GB, and Sindh regions, respectively.

Figure 3a indicates that the monthly area average precipitation was 47.13 mm with a standard deviation of 38.26 mm and the maximum (minimum) precipitation was recorded in the month of July 1978, 2010, and 1988 (November 1998 and December 1999), respectively. Figure 3b–e indicates that the monsoon season received the highest share of precipitation, accounting for 45% of the annual total. The winter and the pre-monsoon seasons accounted for around 30 and 20% of annual total, respectively. The least amount of precipitation was observed in the post-monsoon season accounting for approximately 5% of annual total. Figure 3f indicates that the annual area average precipitation is about 559.39 mm with a standard deviation of 82.49 mm (see Table 2 also) and the maximum (minimum) precipitation was recorded in 1992, 1994, and 1976 (2002), respectively.

4.2 Percentile analysis

4.2.1 Daily precipitation

The percentile analyses were performed for detection of changes in extremely dry to extremely heavy thresholds at daily timescale using Eq. (1). Figure 4 displays the percentile changes between the two half periods with maximum positive (negative) change in extremely heavy threshold in AJK (KPK) region. Positive percentile changes were observed in extremely heavy precipitation threshold in GB and AJK regions, whereas partially positive change was observed in the above normal threshold of AJK region. Negative percentile changes were observed in approximately all the thresholds in KPK, Punjab, Balochistan, and Sindh regions.

4.2.2 Monthly precipitation

Figure 4 displays maximum positive (negative) change in extremely heavy threshold in GB (AJK) region at monthly timescale. Positive percentile changes were observed in the above normal and extremely heavy thresholds in GB region, and in normal threshold in Sindh region. Negative percentile changes were observed approximately in all the thresholds in AJK, Balochistan, KPK, and Punjab regions.

4.2.3 Seasonal precipitation

Figure 4 displays the maximum positive (negative) change in dry (extremely heavy) threshold in AJK region during the winter season. Positive percentile changes were observed in extremely dry and dry thresholds in AJK region, all thresholds in Sindh region, in above normal and extremely heavy thresholds in Punjab region, and in extremely dry, dry, and normal thresholds in GB region. Negative percentile changes were observed in all the thresholds in Balochistan and KPK regions.

Given the location of Pakistan in subtropics, changes in extremely heavy percentiles are linked with the dynamics of 200 hPa zonal wind/subtropical jet stream. Figure 5a, b shows the zonal wind for the period of 1976–1994 and 1995–2013, respectively, whereas Fig. 5c shows the difference of zonal wind between 1976–1994 and 1995–2013. Positive changes were observed and the intensity of zonal wind increased in the later half. Figure 5d shows the changing trend of zonal wind for the period of 1995–2013. A positive change of 0.10 to 0.15 m/s per year over most of Pakistan is evident. During winter season, subtropical jet strengthens and usually lies between 20° N and 50° N. Increasing trends of zonal wind support the increasing precipitation in extreme heavy percentiles for entire Pakistan.

Earlier, Cannon et al. (2015) have studied the relationship of extremely heavy precipitation (85th percentile) during

Table 3 Precipitation distribution across all the six administrative regions on monthly, seasonal (winter, pre-monsoon, monsoon, and post-monsoon), and annual timescales for the studied period 1976–2013

Region	Monthly (%)	Winter (%)	Pre-monsoon (%)	Monsoon (%)	Post-monsoon (%)	Annual (%)
GB	6.51	7.57	12.10	3.88	8.63	6.46
AJK	38.77	38.74	38.08	38.35	37.68	38.11
KPK	24.27	28.79	25.37	20.02	31.79	24.58
Punjab	18.60	13.41	15.73	23.79	13.64	18.89
Balochistan	6.87	9.61	6.22	5.44	5.44	6.98
Sindh	4.98	1.87	2.51	8.52	2.83	4.98

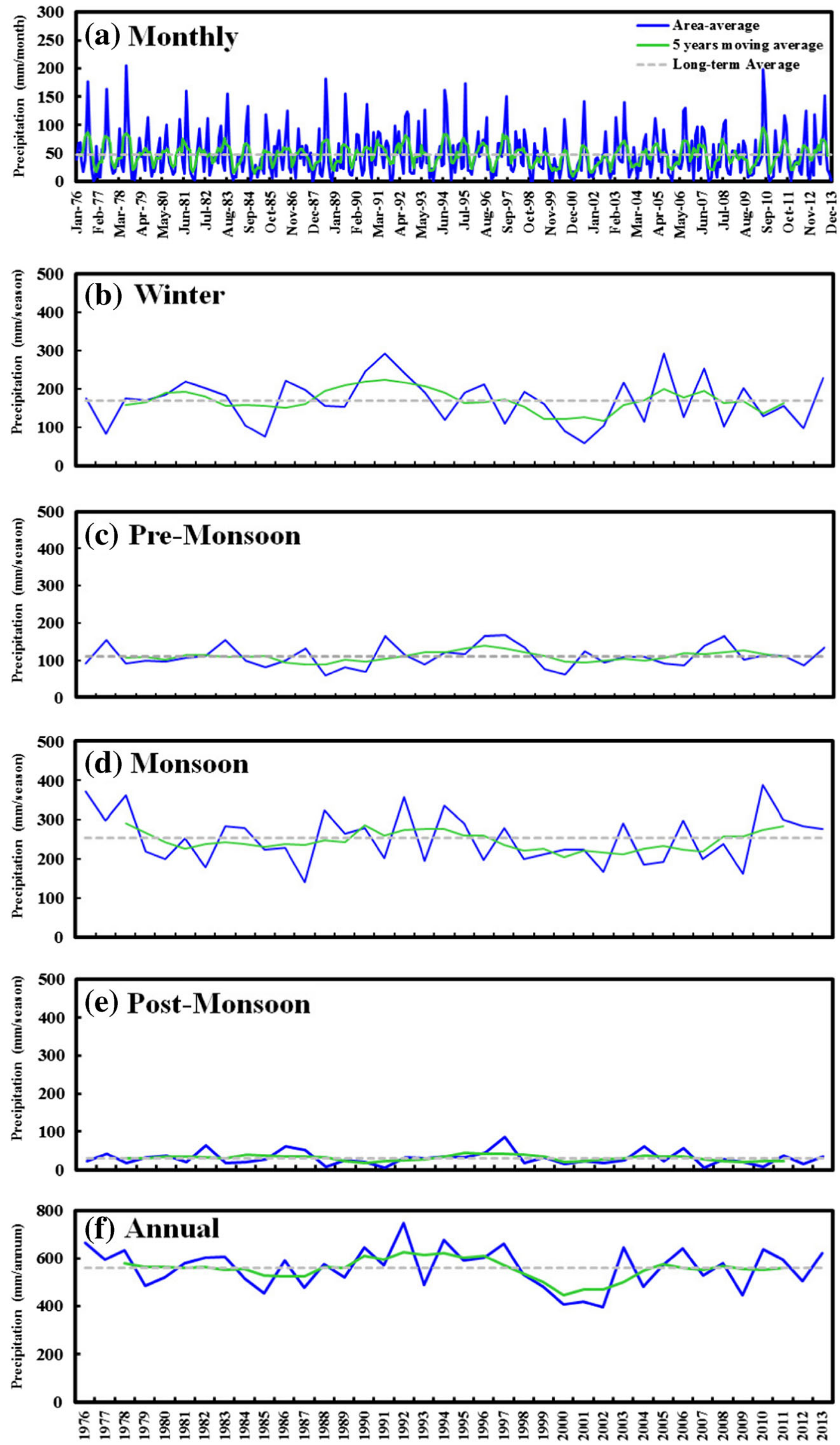


Fig. 3 Time series of all Pakistan area average precipitation on **a** monthly, **b** winter, **c** pre-monsoon, **d** monsoon, **e** post-monsoon, and **f** annual timescales. Area average, 5 years moving average and long-term average precipitation for the entire study period is displayed in each panel

winter season in the Western Himalaya region that includes parts of northern Pakistan with the subtropical jet stream, moisture flux, and 200 hPa geopotential height for an overlapping period of 10 years (1998–2007) mainly using satellite and gridded datasets. Cannon et al. (2015) detected strengthening of subtropical jet in late 1980s, 1990s, and early 2000s, using a reanalysis dataset. Current study also covers Western Himalaya region for the period of 38 years, it is noted that extremely heavy percentile threshold in northern parts of Pakistan including GB, AJK, and some areas of KPK depicted similar increasing behavior of precipitation. The upper level westerly jet is thus considered as an important factor for lower level low- and high-pressure systems development, and therefore, it regulates the strength and position of winter season precipitation over high mountains in Asia (Cannon et al. 2015, 2016a; Dimri et al. 2015). For instance, Dimri et al.

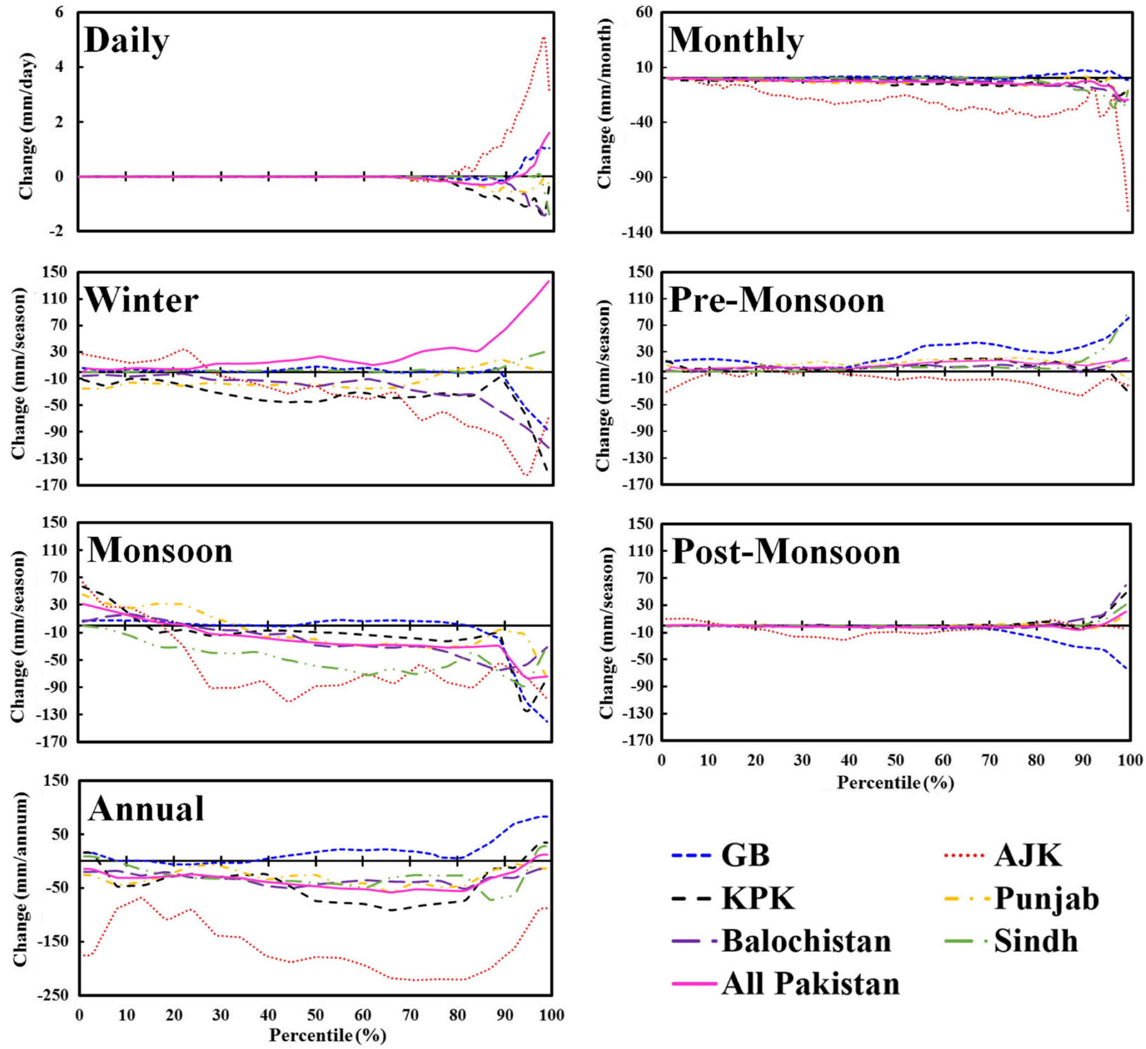


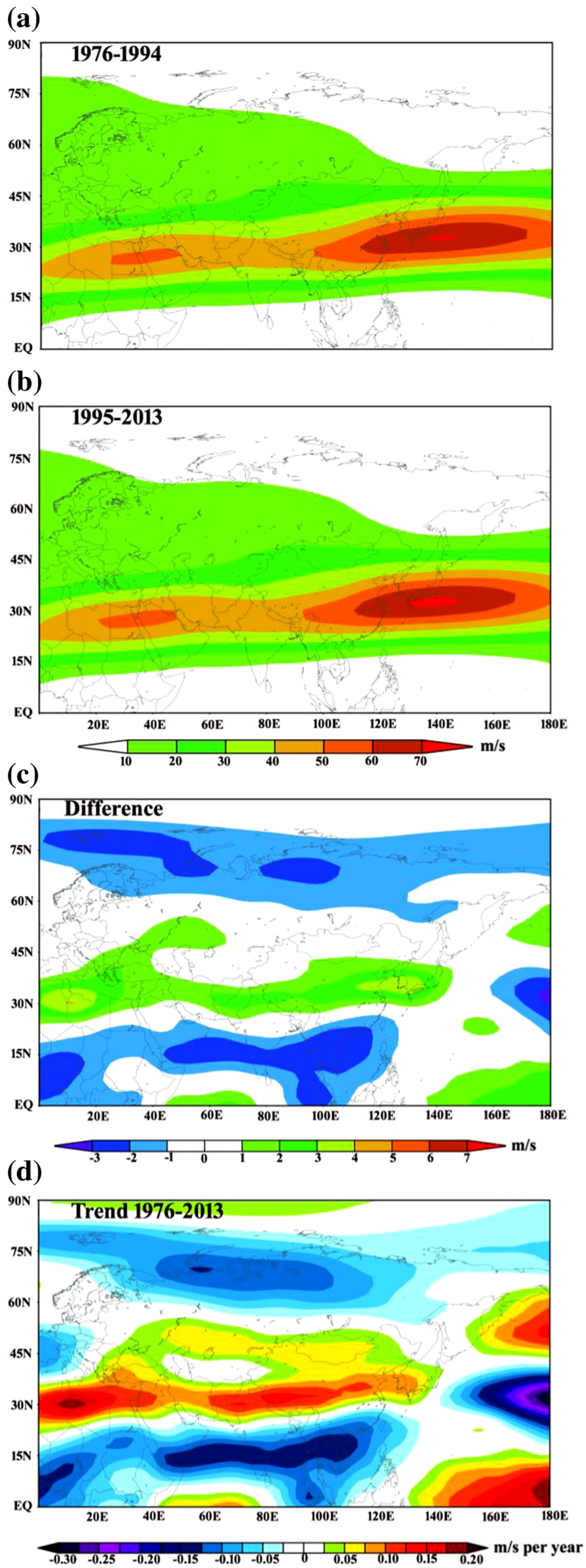
Fig. 4 Daily, monthly, seasonal (winter, pre-monsoon, monsoon, and post-monsoon), and annual timescales area average precipitation percentile change over all six administrative regions including all Pakistan, between the two half periods (1976–1994 and 1995–2013)

(2015) observed an intensification of subtropical jet stream during surplus precipitation years in Karakoram Himalayas.

A maximum positive (negative) change was observed in extremely heavy (above normal) threshold in Sindh (AJK) region during pre-monsoon season. Positive percentile changes were observed in approximately all the thresholds in GB, Balochistan, Punjab, and KPK regions. Negative percentile changes were observed in all the thresholds in AJK region. During pre-monsoon season, early monsoon onset shift causes extreme precipitation events (Latif and Syed 2015; Latif et al. 2016). A maximum positive (negative) change in extremely dry (extremely heavy) threshold was observed in AJK (GB) region during monsoon season. Positive percentile changes were observed in all the thresholds in GB region except few negative percentile changes in the above normal and extremely heavy precipitation threshold. Positive percentile changes were observed in extremely dry and dry precipitation thresholds in AJK, KPK, Balochistan, and Punjab regions and negative percentile changes were observed in all the thresholds in Sindh region.

Extremely heavy precipitation events occur due to enhanced convective activity. Positive and negative percentile changes during monsoon season are connected with many factors including zonal and meridional moisture transport, circumglobal teleconnections (CGT) patterns, and jet stream variability (Saeed et al. 2011; Latif et al. 2016). The percentile changes from extremely dry to extremely heavy thresholds are due to regional or global climate changes eventually affect the water resources of the country (see for instance, Maida and Ghulam 2011).

A maximum positive (negative) change was recorded in extremely heavy threshold in Balochistan (GB) region during post-monsoon season. Positive percentile changes were observed in extremely dry precipitation thresholds in AJK region, whereas in extremely heavy precipitation threshold in Balochistan, KPK, Sindh, and Punjab regions.



◀ **Fig. 5** The winter season spatial distribution of NCEP/NCAR zonal wind at 200 hPa for **a** 1976–1994 and **b** 1995–2013. Panel **c** displays the difference between two periods 1976–1994 and 1995–2013, whereas panel **d** displays the zonal wind trends for entire period (1976–2013)

4.2.4 Annual precipitation

Figure 4 displays the maximum positive (negative) change in extremely heavy (above normal) threshold in GB (AJK) region on annual timescale. Positive percentile changes were observed in extremely dry, normal, above normal, and extremely heavy precipitation thresholds in GB region, and in extremely dry and heavy precipitation thresholds in both KPK and Sindh regions. Negative percentile changes were observed in normal and above normal thresholds, whereas in all thresholds in AJK, Balochistan, and Punjab regions.

Extremely dry to extremely heavy thresholds have serious implications and consequences. Extremely dry and dry percentiles reflect the drought conditions and thus needs special attention, since country's economy is dependent on agricultural growth and production. On the other hand, high and extremely heavy percentiles cause urban flooding, loss of lives in major cities, heavy infrastructure damages, and suspension of socioeconomic activities. Torrential precipitation surges the soil erosion, land degradation, increases the sediment load in the reservoirs, reduces the storage capacity, and impacts groundwater recharge which leads the country towards water scarcity (Maida and Ghulam 2011).

4.3 Mann-Kendall and Sen's slope estimator trend tests

4.3.1 Daily precipitation

The MK and SSE trend analyses were applied on daily timescale to detect magnitude and direction of trends in precipitation time series for the two halves as well as for entire period of six administrative regions, using Eq. (2) to Eq. (9). Results showed a mixture of positive and negative trends in different administrative regions. Table 4 and Fig. 6a display the statistically significant decreasing trends in Sindh region for the period 1976–1994 using MK test. Table 5 and Fig. 6b display a mixture of increasing and decreasing trends for the period 1995–2013. Table 6 and Fig. 6c display significant decreasing trends in four administrative regions, whereas significant increasing trends were observed in Sindh region for the period 1976–2013. Significant decreasing trends were also observed for entire Pakistan. Figure 6d displays the change in Z_{mk} between two time periods.

4.3.2 Monthly precipitation

The results of MK test for the periods 1976–1994, 1995–2013, and 1976–2013 showed a blend of increasing and

Table 4 Results of trend analysis for daily, monthly, seasonal (winter, pre-monsoon, monsoon, and post-monsoon), and annual timescales precipitation for the study period 1976–1994. The Z_{mk} (Q_{med}) represents the Mann-Kendall (Sen's slope estimator) test. The Q_{med} is in units of mm/day for daily timescale and so on

Region	Test	Daily	Monthly	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
GB	Z_{mk}	− 0.007	0.047	0.310	0.111	0.216	0.000	0.298
	Q_{med}	0.000	0.012	2.930	1.308	2.075	0.000	3.876
AJK	Z_{mk}	− 0.004	0.008	0.263	− 0.170	− 0.193	− 0.099	− 0.018
	Q_{med}	0.000	0.013	9.733	− 4.242	− 9.851	− 0.633	− 0.530
KPK	Z_{mk}	− 0.016	0.012	0.216	− 0.064	− 0.146	0.029	0.099
	Q_{med}	0.000	0.015	5.113	− 0.757	− 1.697	0.278	4.064
Punjab	Z_{mk}	− 0.015	− 0.019	− 0.088	− 0.123	− 0.123	− 0.287	− 0.099
	Q_{med}	0.000	− 0.016	− 1.275	− 1.296	− 4.090	− 1.154	− 2.213
Balochistan	Z_{mk}	− 0.017	− 0.008	0.029*	0.135	− 0.064	− 0.236	0.064
	Q_{med}	0.000	− 0.001	0.734	0.775	− 0.801	− 0.330	1.334
Sindh	Z_{mk}	− 0.035**	− 0.086	− 0.099	− 0.135	− 0.111	− 0.287	− 0.170
	Q_{med}	0.000	− 0.001	− 0.348	− 0.233	− 2.043	− 0.303	− 6.006
All Pakistan	Z_{mk}	− 0.017	0.002	0.193	0.006	− 0.088	− 0.041	− 0.006
	Q_{med}	0.000	0.001	2.808	0.042	− 1.705	− 0.154	− 0.082

The *(**) shows the statistically significant trends at the 5% (1%) significance level

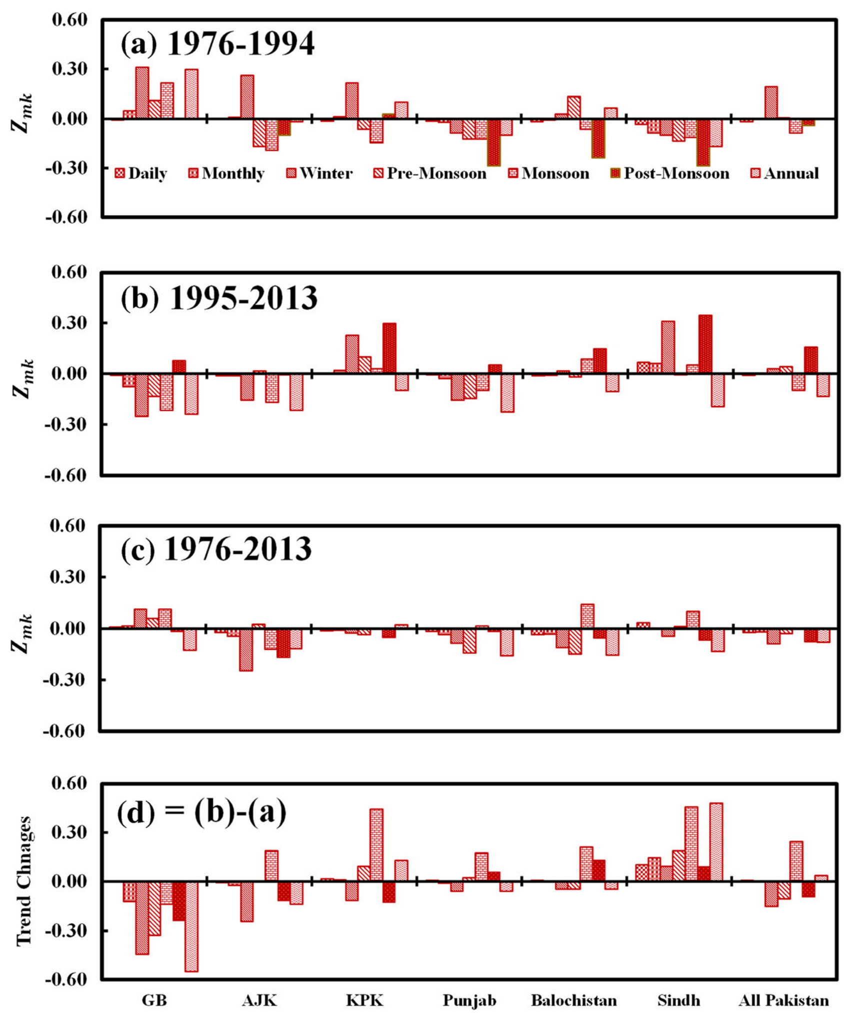


Fig. 6 The Z_{mk} for **a** 1976–1994, **b** 1995–2013, and **c** 1976–2013 on daily (mm/day), monthly (mm/month), seasonal (mm/season), and annul (mm/annum) timescales, whereas **d** displays the change in Z_{mk} between the two time series (1976–1994 and 1995–2013)

Table 5 Same as Table 4 except for the period 1995–2013

Region	Test	Daily	Monthly	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
GB	Z_{mk}	− 0.009	− 0.075	− 0.135	− 0.216	0.076	− 0.240	− 0.251
	Q_{med}	0.000	− 0.021	− 1.286	− 2.658	0.244	− 0.510	− 4.009
AJK	Z_{mk}	− 0.012	− 0.014	0.018	− 0.170	− 0.006	− 0.216	− 0.158
	Q_{med}	0.000	− 0.022	0.811	− 3.074	− 0.590	− 2.348	− 8.483
KPK	Z_{mk}	0.000	0.020	0.099	0.029	0.298	− 0.099	0.228
	Q_{med}	0.000	0.021	4.437	0.198	3.880	− 0.996	8.167
Punjab	Z_{mk}	− 0.007	− 0.029	− 0.146	− 0.099	0.053	− 0.228	− 0.041
	Q_{med}	0.000	− 0.020	− 2.731	− 1.698	1.973	− 0.706	− 1.550
Balochistan	Z_{mk}	− 0.011	− 0.008	− 0.018	0.088	0.146	− 0.106	0.018
	Q_{med}	0.000	0.000	− 0.236	0.880	1.171	− 0.067	0.314
Sindh	Z_{mk}	0.069	0.060	− 0.006	0.053	0.345*	− 0.196	0.310
	Q_{med}	0.000	0.000	− 0.146	0.217	8.521	− 0.011	8.555
All Pakistan	Z_{mk}	− 0.011	− 0.003	0.041	− 0.099	0.158	− 0.135	0.029
	Q_{med}	0.000	− 0.002	0.745	− 0.679	2.259	− 0.685	1.699

decreasing trends on monthly timescale for six administrative regions. Increasing (decreasing) trends were observed in the northern and northwestern parts of the country for the period 1976–1994. Both the studied periods showed increasing trends in the northern and southeastern parts of the country. Results of SSE revealed highest (lowest) slope magnitude with slight increasing (decreasing) trends in KPK (Punjab) region for the period 1976–1994. Highest (lowest) slope magnitude with slight increasing (decreasing) trend was observed in GB (AJK and KPK) region for the period 1976–2013.

4.3.3 Seasonal precipitation

Increasing trends using MK test were observed in northern and northwestern parts along with statistically significant results in southwestern part of the country for the period 1976–1994 and similar trends were observed in AJK and KPK regions for the period 1995–2013 during winter season. For the studied period 1976–2013, increasing trends were also noticed in GB, AJK, and Sindh regions (these results are consistent with the description given in subsection 4.2.3). Like monthly timescale analysis, results of SSE were consistent with the results of MK test for winter season. The westerly extratropical jets, including the lows originating from the Mediterranean region, cause precipitation during winter season (Syed et al. 2010; Dimri et al. 2015).

The MK test results showed increasing trends for the period 1976–1994 in north and southwestern parts of the country, and similar trends were also observed in KPK, Balochistan, and Sindh regions for the period 1995–2013 during pre-monsoon

Table 6 Same as Table 4 except for the entire period 1976–2013

Region	Test	Daily	Monthly	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
GB	Z_{mk}	0.010	0.017	0.061	0.115	− 0.016	− 0.125	0.112
	Q_{med}	0.000	0.002	0.307	0.753	− 0.053	− 0.136	0.598**
AJK	Z_{mk}	− 0.021**	− 0.043	0.024	− 0.121	− 0.166	− 0.115	− 0.246
	Q_{med}	0.000	− 0.035	0.459	− 1.252	− 3.277	− 0.600	− 7.173
KPK	Z_{mk}	− 0.013**	− 0.010	− 0.036	− 0.004	− 0.050	0.021	− 0.024
	Q_{med}	0.000	− 0.005	− 0.685	− 0.075	− 0.431	0.171	− 0.398
Punjab	Z_{mk}	− 0.016**	− 0.035	− 0.141	0.016	− 0.016	− 0.158	− 0.084
	Q_{med}	0.000	− 0.013	− 1.357	0.090	− 0.381	− 0.305	− 1.495
Balochistan	Z_{mk}	− 0.033**	− 0.032	− 0.147	0.144	− 0.053	− 0.155	− 0.110
	Q_{med}	0.000	− 0.004	− 0.777	0.495	− 0.297	− 0.080	0.342
Sindh	Z_{mk}	0.033**	0.001	0.011	0.102	− 0.067	− 0.131	− 0.044
	Q_{med}	0.000	0.000	0.029	0.144	− 0.718	0.000	− 0.578
All Pakistan	Z_{mk}	− 0.021**	− 0.019	− 0.027	0.081	− 0.075	− 0.078	− 0.087
	Q_{med}	0.000	− 0.006	− 0.439	0.325	− 0.543	− 0.154	− 0.737

season. Increasing trends were observed in all regions except AJK and KPK for the period 1976–2013. Nearly similar results were obtained using SSE with a slight change in slope magnitude. Pre-monsoon season precipitation trends depend upon many factors including monsoon onset early shift (Latif and Syed 2015).

Monsoon season plays a significant role in precipitation pattern and MK test revealed increasing trends in northern part of the country during the period 1976–1994. Similar trends were also observed in all regions except AJK along with statistically significant trends in Sindh region for the period 1995–2013. Increasing precipitation trends for all regions for the period 1995–2013 indicate cumulative moisture transport relative to the earlier half. Predominant precipitation is received in the central and northern parts of the country. Monsoon precipitation is linked with the variations in the zonal and meridional moisture transport originating from Bay of Bengal and Arabian Sea (Latif and Syed 2015; Latif et al. 2016). Increasing moisture transport intensifies the precipitation and vice versa. The extratropical CGT patterns in the northern hemisphere enhance precipitation over Pakistan (Saeed et al. 2011; Syed et al. 2010). The eastward propagation of mid-latitude wave associated with CGT also plays a role in monsoon variability (Saeed et al. 2011).

The MK test results showed increasing trends in KPK region only for the period 1976–1994 during post-monsoon season. Decreasing trends for the period 1995–2013 were observed over the entire studied area, which indicates decreasing post-monsoon precipitation in GB and KPK regions in the later half period in comparison with the earlier half period. Less precipitation was received during post-monsoon season with the early withdrawal of monsoon; however, precipitation during this season is also dependent on convective systems (Maida and Ghulam 2011).

4.3.4 Annual precipitation

The MK test results showed increasing trends in KPK and Balochistan regions for both the periods. Annual analysis revealed decreasing (increasing) trends for the period of 1976–1994 (1995–2013) for all Pakistan, indicating frequent and intense precipitation. Increasing (decreasing) slopes or trends were observed in KPK (Sindh) region for the period of 1976–1994 and in KPK and Sindh (AJK) regions for the period 1995–2013. The analysis further revealed that the slope magnitude in AJK decreases more as compared to rest of the regions for the period 1976–2013.

Cumulatively, both methods of estimating the trends on various spatiotemporal scales indicate considerable variability in precipitation over Pakistan. Furthermore, the two different techniques captured dissimilar aspects of variability in precipitation at multiple spatiotemporal scales. However, the results obtained using both MK and SSE tests displayed a decent similarity too. Similar results were also obtained by Gocic and Trajkovic (2013), Tabari and Marofi (2011), and Tabari et al. (2011). Thus, an analysis of relationships of physical behavior of precipitation with other atmospheric/oceanic motions such as teleconnections seems relevant.

4.4 Teleconnections

The teleconnections among circulation indices (IOD, NAO, AO, ENSO, PDO, AMO, and QBO) and the area averaged precipitation over six administrative regions were computed using Eq. (10) and Eq. (11).

4.4.1 Monthly precipitation

Figure 7 shows existence of positive correlation between the IOD and precipitation in Sindh region, particularly in the coastal areas with very strong CL, and a similar behavior was observed in Balochistan region as well. The positive phase of the IOD also showed correlation with Sindh, Punjab, Balochistan, and AJK regions with very strong to strong CL. The positive (negative) phase of the AO showed correlation with Balochistan (Punjab, Sindh, and AJK) region(s) with strong CL. The NAO showed positive correlation in AJK and KPK regions with very strong CL. The negative phase of the NAO exhibited correlation in KPK, AJK, and Punjab regions. The ENSO exhibited correlation in Balochistan, KPK, and AJK regions. The PDO showed positive correlation in GB, AJK, and Balochistan regions with a very strong, strong, and moderate CL, respectively. The correlation of AMO was observed on Punjab region with very strong CL. The QBO (30 hPa) and precipitation of AJK region exhibited positive correlation with moderate CL.

4.4.2 Seasonal precipitation

The relationship of positive (negative) phase of AO and the precipitation of Punjab region was observed with moderate CL (strong CL), whereas positive correlation of negative phase of AO was also noticed in Balochistan and KPK regions during winter season as seen in Fig. 7. The ENSO precipitation relationship was noticed in KPK, Punjab, and Sindh regions. The correlation of PDO was observed in GB region with moderate CL. The positive correlation between QBO (30 hPa) and precipitation over all regions except Balochistan was witnessed with strong to moderate CL. The relationship between QBO (50 hPa) and precipitation of KPK, Punjab, AJK, and GB regions was also observed. No relationship of NAO and AMO with precipitation was observed in range of moderate to very strong CL.

The influence of IOD was observed in Punjab, KPK, and AJK regions with very strong CL and low CC, respectively, during pre-monsoon season. The relationship of positive phase of IOD was noticed in KPK region with moderate CL

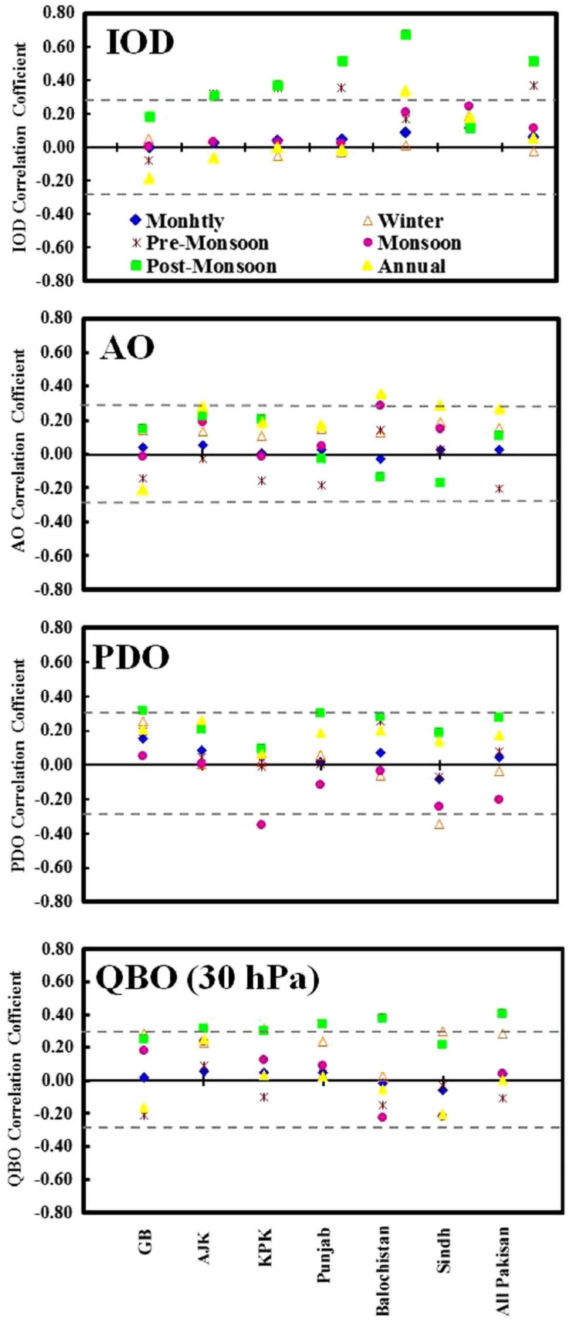


Fig. 7 The correlation coefficients of the circulation indices (IOD, NAO, AO, ENSO, PDO, AMO, and QBO (30 and 50 hPa)) with area averaged regional precipitation on monthly, seasonal (winter, pre-monsoon, monsoon, and post-monsoon), and annual timescales. The dashed horizontal lines in each panel display the 90% CL threshold, except for monthly timescale, for which 90% CL correspondence to CC of 0.079 due to difference in number of observations

and low CC, whereas positive phase of NAO influence was detected in Sindh region with very strong CL and moderate CC. The effect of ENSO was observed in Balochistan, KPK, and Punjab regions with very strong CL and low CC, respectively. The influence of PDO was detected in Balochistan region with moderate CL and low CC; however, positive correlation of AMO was noticed in GB region with very strong CL. The relationship of AO, NAO, and QBO (30 and 50 hPa) was not detected in range of moderate to very strong CL.

The relationship between positive (negative) phases of IOD was noticed in Sindh (KPK) region with moderate CL during monsoon season. A positive low correlation between AO and precipitation of Balochistan region was observed with strong CL, whereas NAO effect was detected in GB region with strong CL and low CC. The influence of positive phase of NAO was detected in Punjab, Sindh, GB, and AJK regions with very strong to moderate CL and moderate CC to low CC, respectively. The correlation of ENSO was observed in KPK, Punjab, and AJK regions with very strong to moderate CL and low CC. The El Niño (La Niña) years cause deficit (surplus) of monsoon precipitation (Syed et al. 2006, 2010; Wang et al. 2011; Hussain and Lee 2016). The influence of PDO was detected in KPK and Sindh regions with very strong and moderate CL, respectively. The correlation of AMO was noticed in Balochistan with moderate CL. The QBO (30 hPa) and QBO (50 hPa) relationship was observed in AJK region with moderate CL and weak CC, and moderate CL and low CC, respectively.

The IOD and ENSO strongly covary with the post-monsoon season precipitation. The relationship of IOD was observed in Balochistan, Punjab, KPK, and AJK regions with very strong to strong CL and moderate to low CC. The influence of positive phase of IOD was also noticed in Balochistan, Punjab, and KPK regions with very strong to strong CL and moderate to low CC. The AO and NAO relationship was noticed in AJK region with moderate to strong CL and low CC, respectively. The correlation between the positive phase of NAO and precipitation of GB region was noticed with moderate CL. The ENSO correlated with the post-monsoon season precipitation over all regions except Sindh with very strong CL. The influence of PDO was observed in GB, Punjab, and Balochistan regions with strong CL and low CC, respectively. The QBO (30 hPa) influence was detected in all regions except Sindh with very strong to moderate CL and low CC. The influence of QBO (50 hPa) was also observed in Balochistan, AJK and Punjab regions with strong to moderate CL and low to weak CC. The influence of AMO was not detected at the range of moderate to very strong CL.

Figure 8 displays an illustrative time series comparison of large-scale ocean and atmospheric circulation indices (IOD, NAO, AO, ENSO, PDO, AMO, and QBO) with the precipitation for the Balochistan region in the post-monsoon season. It was observed that circulation indices with positive (negative) phase lead to heavy (light) precipitation. Furthermore, wet phase years (1980, 1997, 2002, and 2006) of QBO at 30 hPa (except 1982) covary with relatively heavy precipitation in Balochistan. An extended discussion of this aspect is beyond the scope of this paper, and the reader is referred to Rai and Dimri (2017) for further details.

4.4.3 Annual precipitation

The existence of positive correlation of IOD (AO and positive phase of AO) was observed in Balochistan (Balochistan and Sindh) region(s) on annual timescale. The existence of positive correlation of NAO (positive phase of NAO) was noticed in Balochistan and AJK (Punjab, KPK, Balochistan, and Sindh) regions. The relationship between ENSO and precipitation in Balochistan and KPK regions was noticed with very strong to moderate CL, respectively. The PDO and AMO influences were observed in AJK and Balochistan regions with moderate CL. A positive (negative) correlation of QBO at 30 hPa (QBO at 50 hPa) was observed in AJK region with moderate CL.

5 Discussion

The data of 42 stations were analyzed to test the presence of trends and variability, in addition to searching for teleconnections with large-scale ocean and atmospheric circulation indices. For each of the station, analyses were performed on daily, monthly, seasonal (winter, pre-monsoon, monsoon, and post-monsoon), and on annual timescales. Analysis was also performed on area average precipitation of six administrative regions of Pakistan as well as for entire Pakistan. Although the data of 10 years is sufficient for extracting the mean precipitation (Kwarteng et al. 2009), however, in the given study, data of recent 38 years was used for investigating the precipitation variability and trends. An area average maximum (minimum) precipitation resulted in the month of July (November) during monsoon (post-monsoon) season due to large-scale monsoonal currents over Pakistan (Latif et al. 2016). The highest amount of precipitation occurs in summer monsoon season (Hanif et al. 2013; Latif et al. 2016), amounting to 25% (for Balochistan) to 70% (for Sindh) of the annual total precipitation (with a latitude dependence) in agreement with the results of Hussain and Lee (2016). Increasing precipitation trends over higher elevations were also observed in the study of Hanif et al. (2013). The noted precipitation variations and trends have implications for the study area in the context of water scarcity, severe droughts, and extreme flooding and it is therefore recommended to enhance the water storage capacity (Hanif et al. 2013). Maida and Ghulam (2011) support our results that northern part received more precipitation as compared to the southern part of the country.

Both positive and negative changes in spatial distribution of precipitation events were identified. The results of our study support large variations in extreme precipitation events. Thus, our results provide ground truth support for results obtained in Cannon et al. (2015). Percentile changes in different thresholds from extremely dry to extremely heavy precipitation events were identified in different regions and results of Hussain and Lee (2013) support our results. These changes in precipitation patterns also influence the regional and global climate cycle, monsoonal circulation (Latif et al. 2016), ecosystem and forest cover, latitudinal redistribution of precipitation due to anthropogenic forcing (Zhang et al. 2007; Alkama 2014), and may have relevance for the land use practices specially in agricultural lands (Gordon et al. 2010).

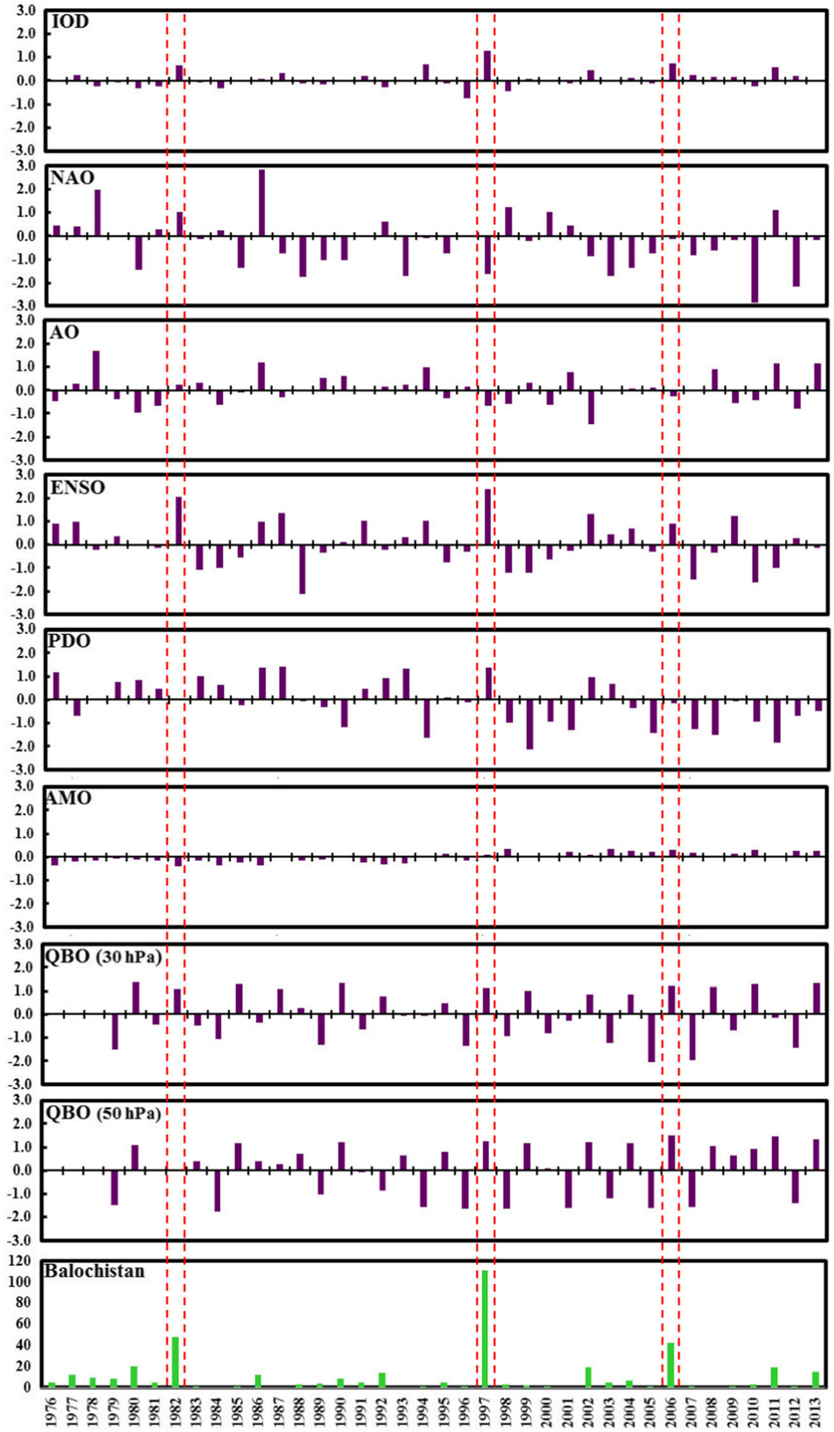


Fig. 8 Upper eight panels show the interannual variability of circulation indices (IOD, NAO, AO, ENSO, PDO, AMO, and QBO (30 and 50 hPa)) for post-monsoon season, whereas lower panel shows the interannual covariability of the precipitation (mm/season) for Balochistan region, for the period of 38 years

The post-monsoon season had the least amount of precipitation, accounting for ~ 5% of the annual total. The precipitation resulted in both winter and pre-monsoon seasons amounts to ~ 30 and ~ 20% of the annual total precipitation, respectively (Syed et al. 2010; Asmat and Athar 2017). Our annual results also confirm Hussain and Lee (2016) findings that the years 1992 and 1994 (2002) received extremely heavy (light) precipitation. Our results show no significant increase in precipitation in KPK and Punjab regions and similar results were also observed by Maida and Ghulam (2011). A mixture of statistically significant and non-significant precipitation trends was observed; however, non-significant results were observed in most of the timescales and analogous results were obtained by Gocic and Trajkovic (2013).

The distant large-scale circulations' influence on precipitation in different regions of Pakistan was established using different circulation indices on monthly, seasonal (winter, per-monsoon, monsoon, and post-monsoon), and on annual timescales, and similar results were also obtained in the previous studies in this region, generally using either interpolated gridded datasets and/or using various climate model outputs or reanalysis datasets (Syed et al. 2006, 2010; Saeed et al. 2011; Syed et al. 2012; Latif et al. 2016). The influence of IOD, NAO, ENSO, and AMO was noticed for entire Pakistan, whereas the influence of positive (negative) phase of IOD (NAO and AO) and AMO was noticed in the Punjab region, NAO (negative phase) and AO impact was observed in AJK region, and the influence of positive (negative) phase of IOD (AO) was noticed in Sindh region at a monthly timescale. On seasonal basis, the influence of ENSO was noticed in all the four seasons with high CL in Balochistan, KPK, Punjab, and AJK regions during monsoon and post-monsoon seasons (Syed et al. 2006; Syed et al. 2010; Saeed et al. 2011; Syed et al. 2012). The influence of IOD, positive AO and NAO phases, ENSO, and AMO was noticed in Balochistan region with strong CL, whereas the impact of positive phase of AO and NAO with strong CL was also detected for entire Pakistan on an annual timescale.

In particular, influence of IOD was observed in the precipitation of coastal, western, and Balochistan regions. A similar behavior was also detected during the monsoon season and relatively more precipitation was observed during the positive phase of IOD. The southeasterly wind transported anomalous moisture from the high-pressure areas over Arabian Sea which resulted in an anticyclone and transported additional moisture from the Arabian Sea to the coastal and southwestern parts of Pakistan and the Balochistan region during positive IOD phases. Positive phase of IOD may be used for precipitation forecasting during monsoon season (Hussain et al. 2016). The influences of ENSO and PDO on precipitation over Pakistan were found to have a clear impact on monthly, seasonal, and on annual timescales (Saeed et al. 2011). In particular, the El Niño phase of ENSO is the core cause for drought years in the entire country (Saeed et al. 2011; Wang et al. 2011).

6 Summary and conclusions

This paper analyzed the long-term time series of precipitation for 38 years (1976–2013) over the six administrative regions of Pakistan using percentile thresholds for assessing the variability of extremely dry to extremely heavy precipitation events and non-parametric MK and SSE tests for detection of precipitation trends, along with large-scale ocean and atmosphere circulation impacts using data from 42 stations. Following are the conclusions of this study:

- All the six administrative regions exhibited a similar pattern of precipitation distribution with highest (lowest) share in summer monsoon (post-monsoon) season. Highest area average mean seasonal precipitation was recorded in the Sindh region during monsoon season and in the Balochistan region during winter season based on location of stations.
- Positive percentile changes were observed in extremely heavy precipitation threshold in GB and AJK regions at a daily timescale, between the two halves of the study period. Positive percentile changes were also observed in the above normal and extremely heavy precipitation thresholds in GB region, whereas negative percentile changes were observed in all the thresholds in AJK, Balochistan, and KPK regions at a monthly timescale. Positive percentile changes were observed approximately in all the percentile thresholds in GB region during winter, pre-monsoon, and monsoon seasons, whereas during post-monsoon season, positive percentile changes were observed in AJK region in extremely dry thresholds only. Negative percentile changes were observed in all the thresholds in AJK, Balochistan, and Punjab regions at an annual timescale.
- Increasing precipitation trends at monthly timescale were observed in KPK and Sindh regions for the period of 1995–2013. Increasing trends for the period of 1995–2013 were observed, whereas decreasing trends were observed for the periods of 1976–1994 and 1976–2013 on annual timescale for entire Pakistan. Increasing precipitation trends for the period of 1995–2013 were observed in AJK and KPK regions during winter season, in KPK, Balochistan, and Sindh regions during pre-monsoon season, and in GB, KPK, Punjab, Balochistan, and Sindh regions during monsoon season. Increasing precipitation trends were observed for the period of 1995–2013 during monsoon and winter season, whereas decreasing trends were observed in the remaining two seasons, for entire Pakistan. Increasing precipitation trends for the period of 1976–2013 were observed only in pre-monsoon season, whereas decreasing trends were observed in the rest of seasons, for entire Pakistan. The magnitudes and sign of trends vary from region to region and depend on the data period used for analysis. The precipitation trends characterize the longer-term patterns. Most of the regions with increasing annual precipitation trends have also increasing precipitation trends in monsoon season.
- Four circulation indices (NAO, ENSO, PDO, and QBO 50 hPa) influenced on AJK region; three circulation indices (IOD, ENSO, and PDO) exhibited teleconnections with Balochistan region. The NAO and ENSO influenced KPK, whereas IOD and PDO covaried with precipitation in Sindh region. The AMO (PDO) effected Punjab (GB) region with strong CL at monthly timescale. Seasonal timescale teleconnections' analysis indicates that QBO (30 hPa) influenced in five regions, QBO (50 hPa) and

ENSO influenced in four regions, while PDO effected in two regions during the winter season. The ENSO influenced in four regions and IOD effected in three regions during pre-monsoon season. The ENSO and QBO (30 hPa) influenced in three regions each and PDO effected in two regions during monsoon season. During post-monsoon season, ENSO and QBO (30 hPa) influenced in five regions each, whereas IOD affected in four regions. Five circulation indices IOD, AO, NAO, ENSO, and AMO (AO, NAO, PDO, AMO, and QBO 30 hPa) influenced in Balochistan (AJK) region, two circulation indices (NAO and AMO) influenced in GB region, whereas ENSO, QBO (50 hPa), and AO influenced in KPK, Punjab, and Sindh regions, respectively, at an annual timescale.

The current research study describing precipitation variability, trends, and its link with large-scale circulation indices contributes as a confidence building measure for (i) policy makers for adaptation and mitigation of climate change, (ii) irrigation departments for water resources management, (iii) agriculture departments for growth and production assessment, (iv) hydropower generation department for power generation, and (v) disaster management divisions for flood forecasting and handling.

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