Theor Appl Climatol (2014) 116:671–680
DOI 10.1007/s00704-013-0988-8

ORIGINAL PAPER

Changes in precipitation extremes over arid to semiarid and subhumid Punjab, Pakistan

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Received: 30 April 2013 / Accepted: 25 July 2013 / Published online: 9 August 2013

Abstract Asymmetrical monsoons during the recent past have resulted into spatially variable and devastating floods in South Asia. Analysis of historic precipitation extremes record may help in formulating mitigation strategies at local level. Eleven indices of precipitation extremes were evaluated using RClimDex and daily time series data for analysis period of 1981–2010 from five representative cities across Punjab province of Pakistan. The indices include consecutive dry days, consecutive wet days, number of days above daily average precipitation, number of days with precipitation ≥10 mm, number of days with precipitation ≥20 mm, very wet days, extremely wet days, simple daily intensity index, maximum 1-day precipitation quantity, maximum 5 consecutive day precipitation quantity, and annual total wet-day precipitation. Mann-Kendall test and Sen's slope extremes were used to detect trends in indices. Droughts and excessive precipitation were dictated by elevation from mean sea level with prolonged dry spells in southern Punjab and vice versa confirming spatial trends for precipitation extremes. However, no temporal trend was observed for any of the indices. Summer in the region is the wettest season depicting contribution of monsoons during June through August toward devastating floods in the region.

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1 Introduction

Changes in precipitation extremes have received enormous attention since many regions worldwide have experienced significant variations in climate extremes during the past few decades (Easterling et al. 2000). This raises the question as to whether extreme climate events are truly increasing or this is only a perceived increase exacerbated by enhanced media coverage or both (Karl and Easterling 1999). In the wake of 2010 floods in China, India, and Pakistan, 2011 flood in Sind province of Pakistan, and 2012 flood in Southern Punjab, Sind, and Baluchistan provinces of Pakistan, experts believe that the changing patterns of monsoon will severely affect the ecosystems in Pakistan during the twenty-first century.

Qian et al. (2011) used monthly precipitation datasets at 160 stations in China as well as winds and humidity data to construct the relationship between six summer dry–wet modes in eastern China and the summer monsoon airflow northwards in East Asia. They found that in the last millennium, northern China has experienced persistent decadal wet periods and persistent decadal dry periods. Basit et al. (2012) investigated the precipitation intensity and patterns during the summer monsoon (July, August, and September) season from the period of 1998 to 2001 over the northern mountainous and southern plain regions of Pakistan. They reported a decreasing precipitation trends during the analysis period; the year 1998 was a dry year and proved to be the beginning of a severe drought lasted up to the year 2000, while in year 2001, the precipitation over some parts of the country exceeded the normal, especially the northern parts of the country observed exceptionally high rainfall rates. Annamalai et al. (2013) investigated the patterns of monsoon rainfall over South Asia by analyzing the All India Monsoon Rainfall Index and found that the patterns of monsoon rainfall had decreasing trends during the last five to six decades.

Literature reports analysis results on changes in climate extremes for many areas of the globe using historical data (e.g., Easterling et al. 1997; Peterson and Vose 1997; Hansen et al. 2001; New et al. 2001; Jones and Moberg 2003; Safeeq et al. 2012; Abbas 2013). Trends in climate extremes during the twentieth century were reported for various regions of China (Zhai et al. 1999), India (Roy and Balling 2004), and in the Caribbean region (Peterson et al. 2002). Frich et al. (2002) reported an increase in the number of warm summer nights, a decrease in the annual number of frost days, and a significant increase in the total wet day rainfall from analysis of a global daily station data. Klein Tank and Können (2003) reported continental-wide wet extremes increase in Europe through analyzing daily data from 1946 to 1999. Moberg and Jones (2005) noted significantly increasing precipitation trends over the twentieth century in winter for both average precipitation intensity and moderately strong events in central and Western Europe. Alexander et al. (2006) noticed a general increase in the precipitation indices worldwide. Tebaldi et al. (2006) reported simulated increases in precipitation intensity with dry periods between precipitation events in a somewhat weaker and less consistent increasing trend during the twentieth and twenty-first centuries. In North America, Griffiths and Bradley (2007) calculated positive trends in the precipitation extreme indices for the region.

Lack of the existing climate change time series data and unavailability of geographic information system-based data processing are among major obstacles in examining the climate extremes in developing countries like Pakistan where high quality long-term meteorological data are unavailable at daily resolution for most parts of the country. The challenge also persists for most of the countries on the globe as the compilation, provision, and upgrading of a globally complete and readily available daily dataset is a very difficult task (Zhang et al. 2005). Increased ability to monitor and detect multidecadal variations and trends is critical to start detecting any observed changes and to understand their patterns (Easterling et al. 2000). Long-term data are needed to evaluate temporal variations in climate extremes.

Literature contains numerous software packages to analyze climate extremes. RClimDex (http://cccma.seos.uvic.ca/ETCCDMI); (Zhang and Yang 2004) written in the statistical software package R is a software package with features for quality control and calculation of indices of precipitation as well as temperature. The quality control of precipitation data in RClimDex is limited only to the identification of negative data values. It is therefore expected of the user to make sure that especially precipitation data is of sufficient quality before utilizing RClimDex to calculate indices (Kruger 2006).

In order to understand recent trends in temporally shifted prolonged monsoons and spatially occurring rainfalls in Indo-Pak subcontinent, it is imperative to explore trends in precipitation extremes over the regions prone to environmental changes both for their geographic location and agricultural production. A better understanding of precipitation patterns is needed to strategies resilient resource management for climate change effect mitigation. The present study reports on the outcomes of analysis of a time series (daily data) precipitation data for five cities randomly selected to represent agriculturally productive and populous Punjab province of Pakistan. The province accommodates over 60 % of Pakistan's total population and produces more than 50 % of the country's agricultural commodities (Abbas 2013).

2 Experimental

2.1 Data collection

Daily precipitation data (1981–2010) were obtained from Pakistan Meteorological Department for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi located across arid to semiarid and subhumid Punjab, Pakistan (Fig. 1). These cities were selected based on their elevation above mean sea level, geographic locations to represent most of the Punjab province, and daily precipitation threshold values (Table 1).

Multan, the third largest city by area and the fifth largest city by population of Pakistan is the geographic center of the country located at bank of the Chenab river in south of Punjab. Lands close to the River Chenab are usually flooded in monsoon season. The city surroundings have flat and alluvial plain making it ideal for agriculture. The area features an arid climate with very hot summers and mild winters. Wheat and cotton are among the major crops of the area. Bahawalnagar, which is among the largest cities of Punjab, represents a riverain area with canal irrigated plains and the desert. The riverain area of the district lies close to the River Satluj. During the summer monsoons, the area is generally inundated by the river water. The area has a very hot and very dry climate in summer. The main crops of Bahawalnagar are cotton, wheat, and rice.

Faisalabad, the third largest metropolis in Pakistan and the second largest in the province of Punjab is irrigated by the lower River Chenab. The city stands in the rolling flat plains

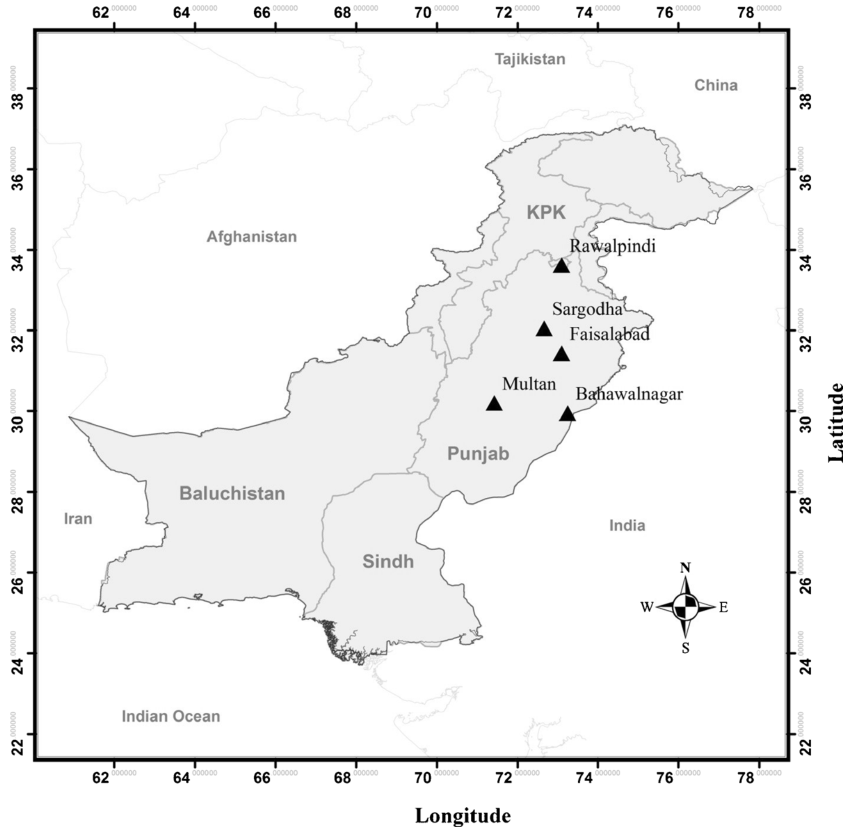

Fig. 1 Five selected cities located across Punjab province of Pakistan

of Punjab. The River Chenab flows about 30 km to the northwest while the River Ravi meanders about 40 km southeast of the city. The lower Chenab canal is the main source of irrigation water, which meets the requirements of 80 % of cultivated land. The soil of Faisalabad comprises alluvial deposits mixed with loess having calcareous characteristics making it very fertile. Due to its high evapotranspiration, Faisalabad features semiarid climate. Neighborhood of the city has seen expanded production of cotton, wheat, sugarcane, vegetables, and fruits, which form 55 % of Pakistan's exports.

Sargodha, the eleventh largest city by population of Pakistan and the fifth largest of the Punjab province is located in the northeast of Pakistan. The River Jhelum flows on its western and northern sides, and the River Chenab lies on its eastern side. Under semiarid environments, Sargodha is largely an agricultural and industrial city. Some of the main crops include citrus, wheat, rice, and sugarcane. For recognition of the best citrus-producing area in the country, it is called the Florida of Pakistan. Rawalpindi, the fourth largest city of Pakistan is geographically located in the rainfed (barani) region of Punjab. The city neighbors bank of Rawal dam on ~8.8 km^2 artificial reservoir of 58.6 million m^3 storage capacity that fulfills needs of drinking for Rawalpindi and Islamabad urban community and irrigates ~202 ha of agricultural lands surrounding the neighborhood of the twin cities. Rawalpindi features a subhumid climate with long and very hot summers and wet winters. Frontal cloud bands bring quite significant rainfall in the winter. Major crops of the area comprise wheat, barley, maize, and millet.

2.2 Quality assurance and quality control of data

Precipitation data were plotted for visual checks and detection of outliers to avoid potential problems that cause changes in

Table 1 Elevation from mean sea level, latitudes, longitude, division on basis of rainfall, and thresholds of daily precipitation for the selected cities

City attributes	Multan	Bahawalnagar	Faisalabad	Sargodha	Rawalpindi
Elevation above sea level, m	122	163	183	187	507
Latitude, degree	30.20	29.95	31.43	32.05	33.62
Longitude, degree	71.43	73.25	73.10	72.67	73.10
Division on the basis of rainfall	Arid	Arid	Semiarid	Semiarid	Subhumid
Daily precipitation threshold, mm	0.552	0.694	1.02	1.20	3.36

the seasonal cycle or variance of the data (Aguilar et al. 2005). For further quality assurance and quality check (QA/QC) of data, RClimDex software developed by the Expert Team on Climate Change Detection Monitoring and Indices (ETCCDMI) at the Climate Research Branch of the Meteorological Service of Canada was used. The software assures that the precipitation data is error free, such as negative precipitation (if any) are marked to be replaced as missing data. Precipitation values above 200 mm were checked to insure that the adjacent values were not set to missing, i.e., to make sure that high values were not due to accumulation over several days (Aguilar et al. 2005). The software was also used to calculate 11 precipitation indices described in Table 2. RClimDex was downloaded along with supporting literature from ETCCDMI website at http://cccma.seos.uvic.ca/ETCCDMI.

2.3 Analysis of trends in indices

The non-parametric Mann–Kendall test (Mann 1945; Kendall 1955) and Sen's slope estimates (Sen 1968) were used to calculate trends in the selected time series of precipitation extremes (Table 2). All the trend analysis were performed using the Excel template application MAKESENS (FMI 2002). MAKESENS uses two different approaches to test for trend in a given time series based on the number of observations. If the number of observations is less than 10, MAKESENS uses the S statistics (Gilbert 1987); otherwise, it uses Z statistics (normal distribution). Detailed descriptions of the program can be found in Salmi et al. (2002). All trends were calculated over the analysis period 1981–2010.

Table 2 The eleven precipitation indices calculated using RClimDex for the selected cities

ID	Indicator name	Descriptions	Units
CDD	Consecutive dry days	Maximum number of consecutive days with rainfall <1 mm	days
CWD	Consecutive wet days	Maximum number of consecutive days with rainfall ≥1.00 mm	days
Rnn	Number of days above nn, mm	Annual count of days when PRCPTOT ≥ nn, mm; where, nn is precipitation threshold values for the selected cities (Table 1)	days
R10	Number of heavy precipitation days	Annual count of days when PRCPTOT ≥10 mm	days
R20	Number of very heavy precipitation days	Annual count of days when PRCPTOT ≥20 mm	days
R95p	Very wet days	PRCPTOT when precipitation >95th percentile	mm
R99p	Extremely wet days	PRCPTOT when precipitation >99th percentile	mm
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCPTOT ≥1.0 mm) in the year	mm day^{-1}
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
RX5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
PRCPTOT	Annual total wet-day precipitation	PRCPTOT in wet days (rainfall ≥1.00 mm)	mm

3 Results and discussion

Most of the cities experienced nonsignificant trends for different indices probably due to the relatively short phase of data in the analysis period and the large year to year variations in precipitation (Aguilar et al. 2005). However, aggregated time series are presented and discussed to highlight several features that will represent the hydroclimatological changes in the study area.

3.1 Dry spells

Dry spells are derived from consecutive dry days index (CDD) that defines prolonged droughts, i.e., consecutive number of days when rainfall was <1.00 mm; it negatively affects fauna and flora of an ecosystem. Multan experienced the most and Rawalpindi experienced the least numbers of dry spells during the analysis period reflecting the maximum length of droughts for the earlier and the minimum length of droughts for the later. The maximum length of dry spells for Multan were ~7 months (209 days) during 1997 and the minimum length of dry spells for Rawalpindi were 18 days during 1998 (Fig. 2). The maximum length of dry spells for Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi were 176 (in 1988), 141 (in 1996), 164 (in 1988), and 71 days (in 1988), respectively. The minimum length of dry spells for Multan, Bahawalnagar, Faisalabad, and Sargodha were 33 (in 1983), 25 (in 1993), 29 (in 2009), and 28 days (in 1983), respectively.

The trends show droughts to be influenced by elevation from mean sea level. Length of dry spells in southern Punjab is very high even with a threshold of 1.00 mm for defining a rainy day. In general, the mean length of the dry spells increases from north to south. With 1.00 mm threshold, average number of dry spells per year over the analysis period of 30 years for Rawalpindi, Sargodha, Faisalabad, Bahawalnagar, and Multan exceeded 44, 66, 82, 94, and 107 days,

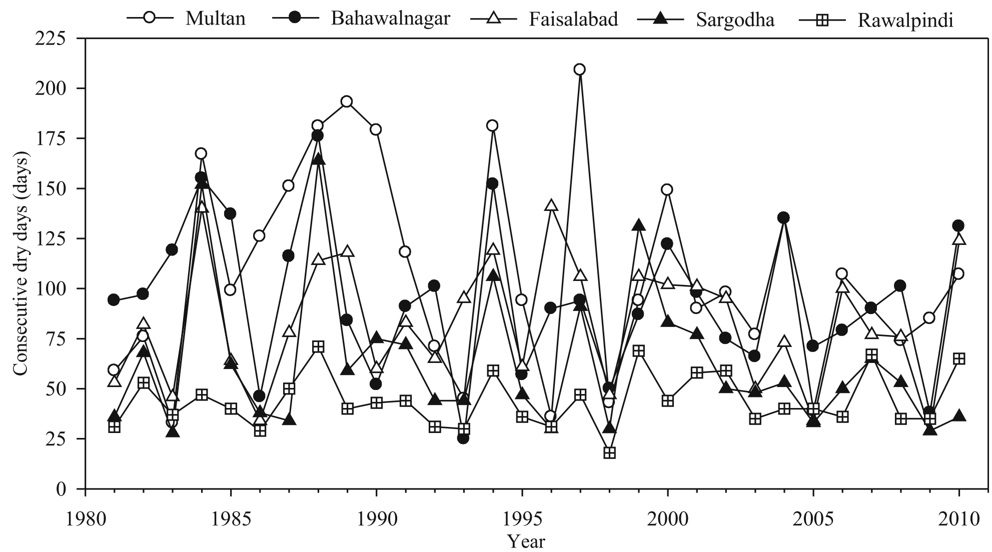

Fig. 2 Averaged anomaly of consecutive dry days (CDD) indices of precipitation among selected regions across Punjab, Pakistan during the base period of 1981–2010

respectively. Converting mean length of dry spells to percent days per year, this corresponds to 12, 18, 23, 26, and 29 % days per year for these cities, respectively.

Droughts significantly affect agricultural production. It is often suggested as the primary cause of root death in many field systems (Huang and Nobel 1992). Above calculated drought spells might have affected root propagation of citrus, mango, wheat, and cotton in the area, especially when Sargodha grows citrus and Multan grows mangos at large scale, and almost all cities grow wheat and cotton in common. Cotton growth in irrigated Multan and Bahawalnagar and wheat growth in almost all the selected cities especially in rainfed areas of Sargodha and Rawalpindi might have faced drought stress during the analysis period because drought conditions near the soil surface are common even though water is usually sufficient to sustain water uptake deeper in the soil profile.

3.2 Wet spells

Consecutive wet days index (CWD) defines wet spells, i.e., consecutive number of days when rainfall was ≥1.00 mm that support fauna and flora of an ecosystem. Contrary to CDD, Rawalpindi experienced the maximum number of wet spells than the other cities during the analysis period confirming the comparative minimum length of droughts for Rawalpindi (Fig. 3). The maximum length of wet spells for Rawalpindi, Sargodha, Faisalabad, Bahawalnagar, and Multan was 9 (in 2000 and 2005), 5 (in 1997 and 2003), 7 (in 2004), 7 (in 2005), and 6 days (in 1992), respectively. The minimum length of dry spells was 3 days (in 1985 and 2002) for Rawalpindi and 2 days each for the rest of cities (in 2006 for Sargodha and during more than five different years for other cities). Heavy rains that caused 2010 flood do not stand out as

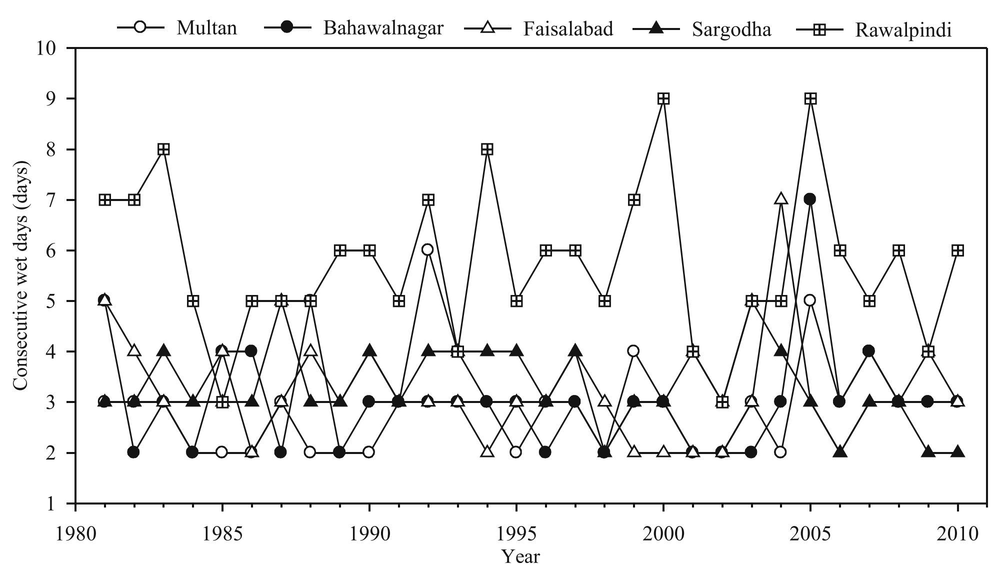

Fig. 3 Averaged anomaly of consecutive wet days (CWD) indices of precipitation among selected regions across Punjab, Pakistan during the base period of 1981–2010

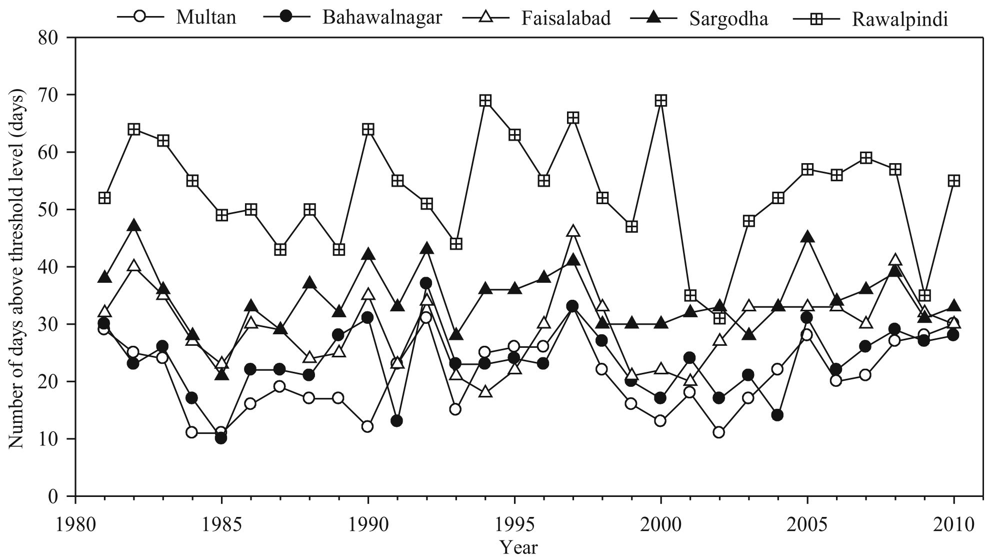

Fig. 4 Averaged anomaly of number of days above threshold level (Rnn) indices of precipitation among selected regions across Punjab, Pakistan during the base period of 1981–2010

unique in CWD. In fact, the rains that caused this flood occurred away from the selected cities up north in the Himalayas and westward in Sulaiman Range and did not have impact on precipitation indices. This may be due to the similar reason of weakly correlated precipitation indices with number of tropical storms reported by Neumann et al. (1987) or intense tropical storms reported by Landsea (1993) in the Atlantic. The two most highly correlated indices, simple daily precipitation intensity index (SDII) and very wet days (R95p), when compared to the number of intense hurricanes in the Atlantic had coefficient of correlation of 0.41 and 0.42, and their relationship with the number of named storms in the Atlantic was found even weaker (Peterson et al. 2002).

In general, the mean length of wet spells increases from south to north. With 1.00 mm threshold, mean number of wet spells per year over the analysis period of 30 years for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi exceeded 2.90, 3.07, 3.16, 3.34, and 5.73 days, respectively. Converting mean length of wet spells to percent days per year, this corresponds to 0.79, 0.84, 0.87, 0.92, and 1.57 %, respectively. Such a lowest percentage of wet spells in the region confirms significant drought during the analysis period.

On contrary to CDD, Multan experienced the least and Rawalpindi experienced the most numbers of CWD during the analysis period reflecting the lowest number of monsoon rains for the earlier and the highest number of events for the latter. Rawalpindi also experienced more temporal variations in CWD than any other city. Overall, more variations in CWD occurred in subhumid region (Rawalpindi) as compared to semiarid and arid regions. This trend reflects that rains in Punjab are dictated by southwest monsoon winds from India originating from the Bay of Bengal. Southern monsoon winds that are generated from Arabian Sea and mostly hit Sind and Baluchistan do not significantly influence Punjab.

3.3 Above average precipitation days

Number of days above threshold levels (Rnn), given in Table 1, of each city showed mixed temporal and spatial (nonsignificant) trends. The maximum Rnn (69 days) occurred for Rawalpindi

Table 3 Annual attributes of heavy and very heavy precipitation days (R10 and R20, respectively) for the selected cities and analysis period

Days	Multan	Bahawalnagar	Faisalabad	Sargodha	Rawalpindi
R10					
Minimum	2 (1991)	2 (1985)	5 (1999)	10 (1985–87, 94, 95)	17 (2002)
Maximum	13 (2010)	20 (1989)	20 (1997)	25 (1992)	45 (1982)
Mean	6.27	8.07	11.8	15.6	34.1
Percent	1.72	2.21	3.24	4.27	9.35
R20					
Minimum	1 (1984, 87, 91, 00, 02, 06, 09)	0 (1981, 85, 99)	3 (1982, 85, 94, 98, 99, 02, 07, 09)	3 (1987)	7 (2009)
Maximum	8 (2010)	9 (1992)	11 (1981)	14 (2001, 05, 07)	31 (2007)
Mean	3.23	3.50	5.43	7.88	19.5
Percent	0.89	0.96	1.49	2.16	5.34

Table 4 Annual attributes of very wet and extreme wet days (R95p and R99P, respectively) and simple daily intensity index (m day^{-1}) for the selected cities and analysis period

Days	Multan	Bahawalnagar	Faisalabad	Sargodha	Rawalpindi
R95p					
Minimum	0 (1987, 89, 91, 96, 98, 00, 02, 04, 06, 08, 09)	0 (1981, 82, 84, 85, 87, 91, 99–02, 04–06, 08, 10)	0 (1982, 85, 86, 93, 95, 96, 99, 00, 04)	0 (1986, 93, 94, 95, 04)	0 (1986, 05)
Maximum	158.7 (1992)	387 (1995)	417 (1997)	460 (1981)	698 (2007)
Mean	50.3	69.9	98.3	135	338
R99p					
Minimum	0 (Other than 1985, 90, 92, 01, 05, 10)	0 (1990, 92, 93, 95)	0 (Other than 1981, 92, 97, 98, 05, 10)	0 (Other than 1981, 82, 84, 97, 02, 06, 07)	0 (1986–88, 90, 91, 93, 98, 00, 02, 03, 05, 08–09)
Maximum	96.2 (1992)	226 (1995)	244 (1997)	355 (1981)	326 (1983)
Mean	15.6	20.4	28.7	47.7	108
SDII					
Minimum	4.3 (1991)	3.4 (1981)	7 (1999)	7.9 (1994)	9.6 (2009)
Maximum	20.3 (1993)	32.8 (1995)	19.7 (1981)	19 (1981)	22.7 (2007)
Mean	10.3	10.9	11.8	12.7	16.5

during 1994 and 2000 (Fig. 4). The minimum Rnn (10 days) in the region was calculated for Bahawalnagar during 1985. Elevation induced maximum Rnn for Sargodha, Faisalabad, Bahawalnagar, and Multan occurred during 1982 (47 days), 1997 (46 days), 1992 (37 days), and 1997 (33 days), respectively. Similar effect of elevation was also observed on the minimum Rnn which for Rawalpindi, Sargodha, Faisalabad, and Multan were 31 (2002), 21 (1985), 18 (1994), and 11 days (2002), respectively. A gradual decrease in Rnn was noticed for cities in subhumid environments, whereas those in arid environment experienced unexpected variations might be due to variation of monsoon winds in these areas. Trends in Rnn support CWD trends as Rawalpindi experienced the most and Multan experienced the least numbers of Rnn during the analysis period. These results reflect wetter weather during the analysis period as Rnn for Rawalpindi, Sargodha, Faisalabad, Bahawalnagar, and Multan exceeded by 14.5, 10.2, 8.05, 6.47, and 5.78 % of days per year, respectively. This corresponds to respective mean Rnn for above cities slightly exceeding 52, 37, 29, 23, and 21 days per year.

3.4 Heavy and very heavy precipitation days

There was no significant trend in heavy precipitation days (number of days in a year when total precipitation was greater than or equal to 10 mm represented by R10) and very heavy precipitation days (number of days in a year when total precipitation was greater than or equal to 20 mm represented by R20) for any of the selected cities. Annual values of minimum, maximum, mean, and percent of R10 and R20 for the selected cities are given in Table 3. Similar to CDD, CWD, and Rnn, the trends in R10 and R20 were dictated by elevation of cities from mean sea level except few anomalies of Bahawalnagar for minimum and mean values of R20.

There was a spatial trend in number of minimum and maximum R10, which increased with increase in elevation

Table 5 Extremes of monthly maximum 1-day (RX1day) and 5 consecutive days (RX5day) precipitation magnitude along with respective months and years for the five selected cities and analysis period

Monthly extremes	RX1day		RX5day	
	Highest, mm	Lowest, mm	Highest, mm	Lowest, mm
Multan	96.2 (September 1992)	21 (August 2009)	143 (August 2010)	22 (August 2009)
Bahawalnagar	130 (July 1995)	15.5 (July 1981)	188 (July 1995)	22.2 (August 1984)
Faisalabad	180 (July 1981)	25 (June 1982)	208 (August 1997)	40 (June 1982)
Sargodha	177 (Aug. 2000)	29 (July 2007)	233 (August 1997)	45.4 (August 1986)
Rawalpindi	200 (August 1997)	50 (July 2005)	435 (August 1982)	84.6 (March 1993)
Region	200 (August 1997)	15.5 (July 1982)	435 (August 1982)	15.5 (July 1982)

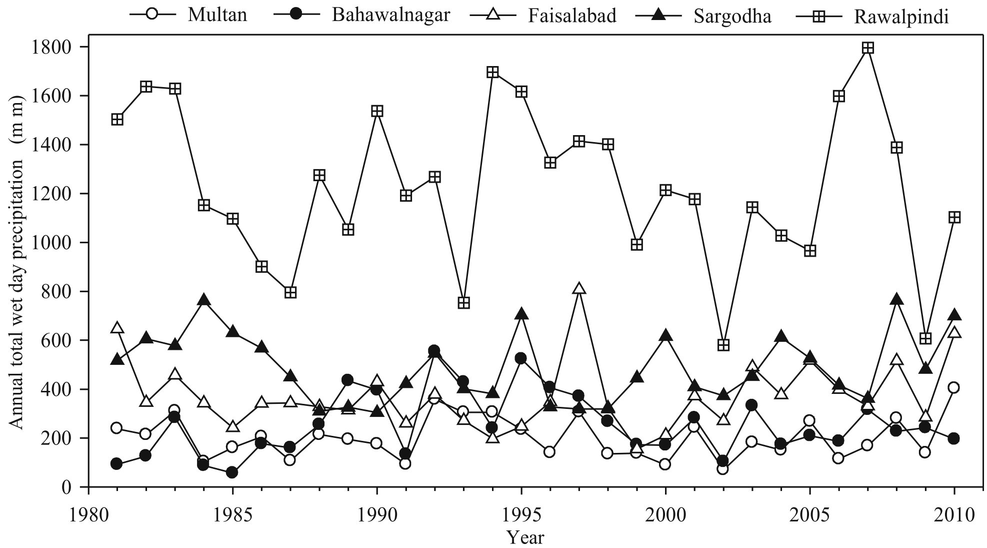

Fig. 5 Averaged anomaly of annual total wet day precipitation (PRCPTOT) for the selected cities and analysis period

of cities from mean sea level with regional minimum and maximum R10 ranging from 2 to 17 days and 13 to 45 days, respectively. However, no temporal significant trend was found in R10 index. For Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi, the respective mean R10 were computed to be 6.27, 8.07, 11.8, 15.6, and 34.1 days that correspond to 1.72, 2.21, 3.24, 4.27, and 9.35 % heavy precipitation days for above cities and the considered analysis period.

Spatial and temporal trends of R20 were similar to those of R10 except for an anomaly in minimum R20 of Bahawalnagar where its value was less than that of Multan (Table 3). Regional minimum and maximum R20 ranged from 0 to 7 days and 8 to 31 days, respectively. For Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi, the respective mean R20 were computed to be 3.23, 3.50, 5.43, 7.88, and 19.5 days that correspond to 0.89, 0.96, 1.49, 2.16, and 5.34 % very heavy precipitation days for above cities and 1981–2010 analysis period.

3.5 Very wet and extreme wet days

Elevation of cities from mean sea level had direct impact on quantity of precipitation produced during very wet days (extracted from precipitation index R95p) with minimum R95p to be zero for all cities in multiple years, maximum R95p 158.7 (1992), 387 (1995), 417 (1997), 460 (1981), and 698 mm (2007), and mean R95p 50.3, 69.9, 98.3, 135, and 338 mm per year for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi, respectively (Table 4). Similar trends were found on quantity of precipitation received during extreme wet days (extracted from precipitation index extremely wet days, R99p) with minimum R99p to be zero for all cities in multiple years, maximum R99p 96.2 (1992), 226 (1995), 244 (1997), 355 (1981), and 326 mm (1983), and mean R99p 15.6, 20.4, 28.7, 47.7, and 108 mm per year for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi, respectively. Mean per year precipitation for the selected cities was over three times greater during very wet days than during extreme wet days except for Sargodha for which maximum amount of precipitation was 2.83 times greater during very wet days than during extreme wet days.

SDII shows the annual total precipitation divided by the total number of days with precipitation above or equal to 1.00 mm (Table 4). Because SDII is a metric for precipitation rate, the average precipitation intensity on very heavy precipitation and extreme wet days would be larger and correspond to those in R20 and R99p. Obvious spatial and no temporal trends in SDII with anomalies for Bahawalnagar support the finding of reports in literature for other regions (Chu et al. 2010).

3.6 Single and multiday precipitation extremes

Patterns of RX1day and RX5day, a rough proxy of extreme monthly precipitation magnitude accumulated over a 1-day and 5 consecutive days periods, respectively, in a year are given in

Table 6 Extremes and mean values of total wet day precipitation (PRCPTOT) for the selected cities and analysis period

PRCPTOT	Multan	Bahawalnagar	Faisalabad	Sargodha	Rawalpindi
Minimum	399 (2010)	553 (1992)	806 (1997)	763 (2005)	1796 (2007)
Maximum	70.4 (2002)	53.6 (1985)	155 (1999)	300 (1987)	580 (2002)
Mean	199.7	251.7	370.2	473	1228

Table 5. Monthly maximum 1-day precipitation for the region ranged from 15.5 mm in July 1981 to 200 mm in August 1997, the two extremes were recorded for Bahawalnagar and Rawalpindi, respectively. This resulted in an anomaly for the lowest RX1day to occur in Bahawalpur, which is 41 m higher in elevation from mean sea level than Multan. Monthly maximum 5-day precipitation for the region ranged from 22 mm in August 2009 to 435 mm in August 1982, the two extremes were recorded for Multan and Rawalpindi, respectively. In general, Rawalpindi experienced the highest RX1day and RX5day extremes. The data depicted summer (June to August) to be the wettest season in the region except for one anomaly when Rawalpindi received 84.6 mm precipitation during 5 consecutive days in spring (i.e., during March 1993). Total quantity of precipitation for 5 consecutive days was not multiple of number of days when compared with maximum 1-day precipitation. These results are in concurrence with the findings of Karl and Knight (1998) who reported that trends in 1-day and multiday heavy precipitation events in the USA and other countries showed a tendency to more days with heavy 24-h precipitation totals.

3.7 Annual total wet day precipitation

Annual total wet day precipitation (PRCPTOT) of each city is shown in Fig. 5 for the analysis period of 30 years. Elevation from mean sea level influenced PRCPTOT. Resultantly, Rawalpindi being in north and in subhumid environments received more precipitation than the rest of cities. Likewise, Multan being in south and in arid environments received the least precipitation than other cities in the study area. For Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi, 2010, 1992, 1997, 2005, and 2007 were the wettest and 2002, 1985, 1999, 1987, and 2002 were the driest years of the analysis period, respectively. This concludes no temporal trend in precipitation, whereas spatial trends are obvious from mean PRCPTOT under the influence of elevation from mean sea level (Table 6).

4 Conclusions

Nonsignificant spatial and no temporal trends were calculated for the selected cities and analysis period. Droughts (CDD) and wet spells (CWD) in the region were dictated by elevations of cities from mean sea level. Resultantly, Multan experienced the most number of droughts and Rawalpindi had the most number of wet spells and vice versa. Overall, wetter weather was observed in the province during the analysis period as Rnn—the number of events when mean values of daily precipitation for Rawalpindi, Sargodha, Faisalabad, Bahawalnagar, and Multan exceeded the historical daily averages by 14.5, 10.2, 8.05, 6.47, and 5.78 % of days per year, respectively, corresponding to respective mean Rnn for above cities slightly exceeding 52, 37, 29, 23, and 21 days per year. Similar to CDD, CWD, and Rnn, the trends in R10 and R20 were dictated by elevation of cities from mean sea level. This resulted in mean per year precipitation quantity for the selected cities to exceed more than three times during very wet days than during extreme wet days. In general, summer months of June through August were the wettest months in the province. Consequently, the wettest (driest) years of the analysis period for Multan, Bahawalnagar, Faisalabad, Sargodha, and Rawalpindi were 2010 (2002), 1992 (1985), 1997 (1999), 2005 (1987), and 2007 (2002), respectively. This confirms no temporal trend in precipitation, whereas spatial trends were obvious from mean PRCPTOT under the influence of elevation from mean sea level.

Acknowledgments Funds for this research were provided by the Higher Commission of Pakistan.

References

Abbas F (2013) Analysis of a historical (1981–2010) temperature record of Punjab province of Pakistan. Earth Interact. doi:10.1175/2013EI000528.1

Aguilar E, Peterson TC, Obando PR, Frutos R, Retana JA, Solera M, Soley J, Garcia IG, Araujo RM, Santos AR, Valle VE, Brunet M, Aguilar L, Alvarez LA, Bautista M, Castanon C, Herrera L, Ruano E, Sinay JJ, Sanchez E, Oviedo GIH, Obed F, Salgado JE, Vazquez JL, Baca M, Gutierrez M, Centella C, Espinosa J, Martinez D, Olmedo B, Espinoza CEO, Nunez R, Haylock M, Benavides H, Mayorga R (2005) Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003. J Geophys Res 110:1–15

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Ambenje P, Rupa-Kumar K, Revadekar J, Griffiths G (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res 111:D05109. doi:10.1029/2005JD006290

Annamalai H, Jan Hafner K, Sooraj P, Pillai P (2013) Global warming shifts the monsoon circulation, drying South Asia. J Clim 26:2701–2718

Basit A, Shoaib SR, Irfan N, Avila R (2012) Simulation of monsoon precipitation over South-Asia using RegCM3. ISRN Meteorology 12:754902. doi:10.5402/2012/754902

Chu P, Chen YR, Schroeder TA (2010) Changes in precipitation extremes in the Hawaiian Islands in a warming climate. J Clim 23:4881–4900

Easterling DR, Horton B, Jones PD, Peterson TC, Karl TR, Parker DE, Salinger MJ, Razuvayev V, Plummer N, Jamason P, Folland CK (1997) Maximum and minimum temperature trends for the globe. Science 277:364–367

Easterling DR, Evans JL, Groisman PY, Karl TR, Kunkel KE, Ambenje P (2000) Observed variability and trends in extreme climate events: a brief review. Bull Am Meteorol Soc 81:417–425

FMI (2002) Detecting Trends of Annual Values of Atmospheric Pollutants by the Mann–Kendall Test and Sen's Slope Estimates: The Excel Template Application MAKESENS. Finnish Meteorological Institute, 2002

Frich P, Alexander LV, Della-Marta P, Gleason B, Haylock M, Klein Tank AMG, Peterson T (2002) Observed coherent changes in climatic extremes during the second half of the twentieth century. Clim Res 19:193–212
Gilbert RO (1987) Statistical methods for environmental pollution monitoring. Van Nostrand Reinhold, New York
Griffiths ML, Bradley RS (2007) Variations of twentieth century temperature and precipitation extreme indicators in the northeast United States. J Clim 20:5401–5417
Hansen J, Ruedy R, Sato M, Imhoff M, Lawrence W, Easterling D, Peterson T, Karl T (2001) A closer look at United States and global surface temperature change. J Geophys Res 106: 23947–23963
Huang B, Nobel PS (1992) Hydraulic conductivity and anatomy of lateral roots of Agave deserti during root growth and drought induced abscission. J Exp Bot 43:1441–1449
Jones PD, Moberg A (2003) Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001. J Clim 16:206–223
Karl TR, Easterling DR (1999) Climate extremes: selected review and future research directions. Climate Change 42:309–325
Karl TR, Knight RW (1998) Secular trends of precipitation amount, frequency, and intensity in the United States. Bull Am Meteorol Soc 79:1107–1119
Kendall MG (1955) Rank correlation methods. Griffin, London
Kruger AC (2006) Observed trends in daily precipitation indices in South Africa: 1910–2004. Int J Climatol 26(15):2275–2285
Klein Tank AMG, Konnen GP (2003) Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99. J Clim 16:3665–3680
Landsea CW (1993) A climatology of intense (or major) Atlantic hurricanes. Mon Weather Rev 121:1703–1713
Mann HB (1945) Nonparametric test against trend. Econometrica 13:245–259
Moberg A, Jones PD (2005) Trends in indices for extremes in daily temperature and precipitation in central and western Europe, 1901-99. Int J Climatol 25:1149–1171
Neumann CJ, Jarvinen BR, Pike AC, Elms JD (1987) Tropical Cyclones of the North Atlantic Ocean, 1871–1986. Natl, Environ. Satell. Data and Inf. Serv., p 186
New M, Todd M, Hulme M, Jones P (2001) Precipitation measurements and trends in the twentieth century. Int J Climatol 21:1889–1922
Peterson TC, Taylor MA, Demeritte R, Duncombe DL, Burton S, Thompson F, Porter A, Mercedes M, Villegas E, Fils RS, Klein Tank A, Martis A, Warner R, Joyette A, Mills W, Alexander L, Gleason B (2002) Recent changes in climate extremes in the Caribbean region. J Geophys Res 107:1–9
Peterson TC, Vose RS (1997) An overview of the Global Historical Climatology Network temperature database. Bull Am Meteorol Soc 78:2837–2849
Qian WH, Zhu YF, Tang SQ (2011) Reconstructed index of summer monsoon dry–wet modes in East Asia for the last millennium. Chin Sci Bull 56:3019–3027
Roy SS, Balling RC Jr (2004) Trends in extreme daily precipitation indices in India. Int J Climatol 24:457–466
Safeeq M, Mair A, Fares A (2012) Temporal and spatial trends in air temperature on the Island of Oahu, Hawaii. Int J Climatol. doi:10.1002/joc.3629
Salmi T, Maatta A, Anttila P, Ruoho-Airola T, Amnell T (2002) Publications on air quality. No 31. Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates. Finnish Meteorological Institute Helsinki, Finland
Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63:1379–1389
Tebaldi C, Hayhoe K, Arblaster JM, Meehl GA (2006) Going to the extremes: an intercomparison of model-simulated historical and future changes in extreme events. Climate Change 79:185–211
Zhai P, Sun A, Ren F, Liu X, Gao B, Zhang Q (1999) Changes of climate extremes in China. Climate Change 42:203–218
Zhang X, Yang F (2004) RClimDex (1.0) User Guide: Climate Research Branch Environment Canada (2004)
Zhang X, Hegerl G, Zwiers FW, Kenyon J (2005) Avoiding inhomogeneity in percentile-based indices of temperature extremes. J Clim 18:1641–1651