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Research Article

Climate Change Indicators and Spatiotemporal Shift in Monsoon Patterns in Pakistan

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Monsoon rainfall is the principle source of fresh water essential for agricultural practices and human sustenance in the Indian subcontinent during summer. This study is primarily designed to analyse the extent of rainfall and temperature variations in Pakistan over the northern monsoon belt by using satellite and ground-based observations. The satellite gridded data for rainfall are acquired from Tropical Rainfall Measuring Mission (TRMM) along with rainfall and temperature data from 15 ground stations of Pakistan Meteorological Department (PMD). Data were analysed to identify changes in climatic parameters and spatiotemporal shift in monsoon precipitation in Pakistan. Analysis shows that there is significant correlation between TRMM and PMD datasets. Decrease in monsoon rainfall is observed during the last two decades. A more pronounced decrease is observed in monsoon rainfall during the years 2010–2017, i.e., 17.58 mm/year accompanied by 0.18°C increase in temperature. A southward spatial shift in monsoon rainfall occurrence (rainfall ≥2.5 mm/day) is observed while an eastward shift in moderate to heavy monsoon rainfall is identified. This study may be helpful for an agricultural country like Pakistan which is heavily dependent on monsoon rainfalls for assessing the impacts of changing monsoon season and to adapt towards changing climate.

1. Introduction

The large variability between commencement and duration of summer monsoon exercises an immense control on socioeconomic parameters like water resources, agriculture, ecosystems, economics, and human health across the South Asia. As large population and growing agriculture sector in South Asia depend on monsoon rainfall patterns, any disruption causes huge concerns. It is vital to explore the response of monsoon dynamics to rising temperature and varying concentrations of greenhouse gases at both scientific and societal level [1–4].

Impending climate change and the impacts it will exert on precipitation distribution patterns pose an imminent threat to aquatic ecosystems around the globe. The Intergovernmental Panel on Climate Change [5] has stated that drought-hit areas might grow in both space and time, and intensity of heavy precipitation events would likely rise as a manifestation of impacts of climate change on fresh aquatic systems. Long-term variations over regional and local scales in the monsoon rainfall over India have significant implications on socioeconomic circles in the region [6]. The Indian subcontinent will be negatively impacted due to heightened deviations in climate extremes, rising temperatures, and significant decrease in summer precipitation over some regions possibly causing water stress by the year 2020 [5].

Indian summer monsoon plays a vital role in hydrological cycle of South Asia serving as a primary source of the total precipitation in this region. Along with the glacial meltdown, the monsoon acts as a backbone for socioeconomic structure of the Indian subcontinent by providing water for key agriculture sector and domestic use. This rainfall system is a part of the global circulation system which helps to regulate the temperature of the Earth by transferring heat from the tropical areas towards higher latitudes [3]. Monsoon enters Pakistan from two different directions; first way is when the south-westerly winds coming from the Bay of Bengal enter Pakistan after travelling along the foothills of Himalayas. Districts of Sialkot, Jhelum, Islamabad, and Lahore in Pakistan receive the first monsoon rains, and these stations are part of Pakistan's northern monsoon belt—main monsoon occurring region of Pakistan. Second pathway is when the southwest winds from Arabian Sea enter Pakistan. The areas which receive rainfall from these wind currents constitute south-eastern region of Pakistan [7].

Long-term studies of monsoon rainfall trends in Pakistan are quite limited. Spatial analysis over Pakistan's geographic zones has indicated that the monsoon precipitation has decreased after 1970s [8]. Since the same monsoon system affects Pakistan and India, some studies from India can have relevance to Pakistan. Rainfall over India displays strong spatial and temporal deviations and huge variations from the mean values. Various studies show overall trend of decline in the monsoon precipitation in many parts of India (e.g., [9–13]). The monsoon activity over the region has been somewhat subdued during recent warming trends [14], as monsoon precipitation decreased by 2.4% in 1979–2009 when compared with the years 1949–1978 [15]. Another regional study on subseasonal scale indicates that there is a decrease in rainfall in July and August over years 1976–2004 in the main as well as south-west monsoon regions of India [11]. Rainfall measurements taken over land depict a decreasing trend in rainfall during 1951–2000 in the subtropics and tropics and an increasing trend in the midlatitudes of the Northern Hemisphere, a consequence linked to the rising levels of greenhouse gases [2, 4].

The trend of significant warming over the Bay of Bengal, the equatorial South Indian Ocean, and Arabian Sea significantly accelerated during the period of years 1971–2002 [11]. While increased surface temperature can lead to increasing intensity of droughts, on the other hand, water holding capacity of air increases by about 7% per 1°C warming, which further causes elevated levels of water vapours in the atmosphere [16]. Additional moisture per unit of ascending movement present in atmosphere weakens atmospheric circulation, causing weakening of monsoon systems [17]. However, the Indian summer monsoon system does not directly depend upon the increase in air temperature as tropical areas have complex systems at play [16].

Length of monsoon rainy season in Pakistan is quite limited in comparison with other countries under the influence of the same monsoon system because Pakistan is situated at the western end of south-west monsoon area. Figure 1 shows the location of Pakistan in the Indian summer monsoon region, and Figure 2 depicts the active rainfall period over Pakistan represented by isohyets. The active period of summer monsoon for Pakistan is one and a half month as compared to four months in India [18]. Two significant features of this monsoon system are (i) regular onset every year from June to September (ii) and the irregular changes in amount of seasonal mean rainfall from one year to another [7]. The summer monsoon system over South Asia is recognized as a fully coupled ocean-land-atmosphere system which involves interactions with mountain ranges of the region too; however, all the feedback and mechanisms involved have not been entirely explored yet [19].

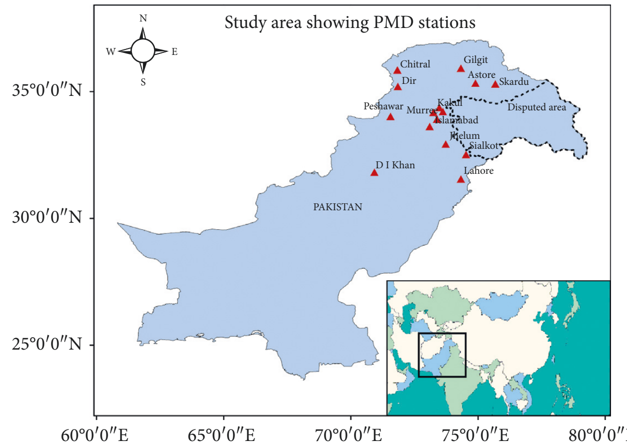


Figure 1: Map of study area showing the location of PMD's meteorological stations (red triangles) constituting the monsoon belt in Pakistan.

The devastating floods of 2010 were a hydrologic and sociologic event of extreme magnitude in Pakistan. Although the event was influenced by many other factors like snowmelt due to rising temperatures and faulty water management practices, the event was primarily marked with an abnormally heavy and prolonged rainfall event. The hardest hit areas include the northern provinces of Khyber Pakhtunkhwa and the State of Azad and Jammu Kashmir with 2000 fatalities [20]. These unusual events gave rise to an interesting debate in scientific and social communities on monitoring and investigating the extreme monsoon precipitation that result in devastating floods. Precipitation measurements by using satellites and weather forecast models may assist in monitoring as well as forecasting the evolution and transport of convective rainfall systems like monsoon [21].

For a country like Pakistan, improvement in management practices for natural water assets is of utmost importance as rainfall is a seasonal phenomenon in the country. In the present study, precipitation trends during both monsoon and postmonsoon seasons in Pakistan are analysed and their link with temperature trends has been investigated by employing ground-based and satellite observations. Therefore, this study becomes vital in order to address the utmost water needs of Pakistan, and it may serve as a baseline for relevant authorities to device better strategies to meet the increasing demand of water as well as mitigate the adverse effects of floods in Pakistan.

2. Materials and Methods

Ground data from meteorological stations have been analysed to study the change in rainfall and temperature during

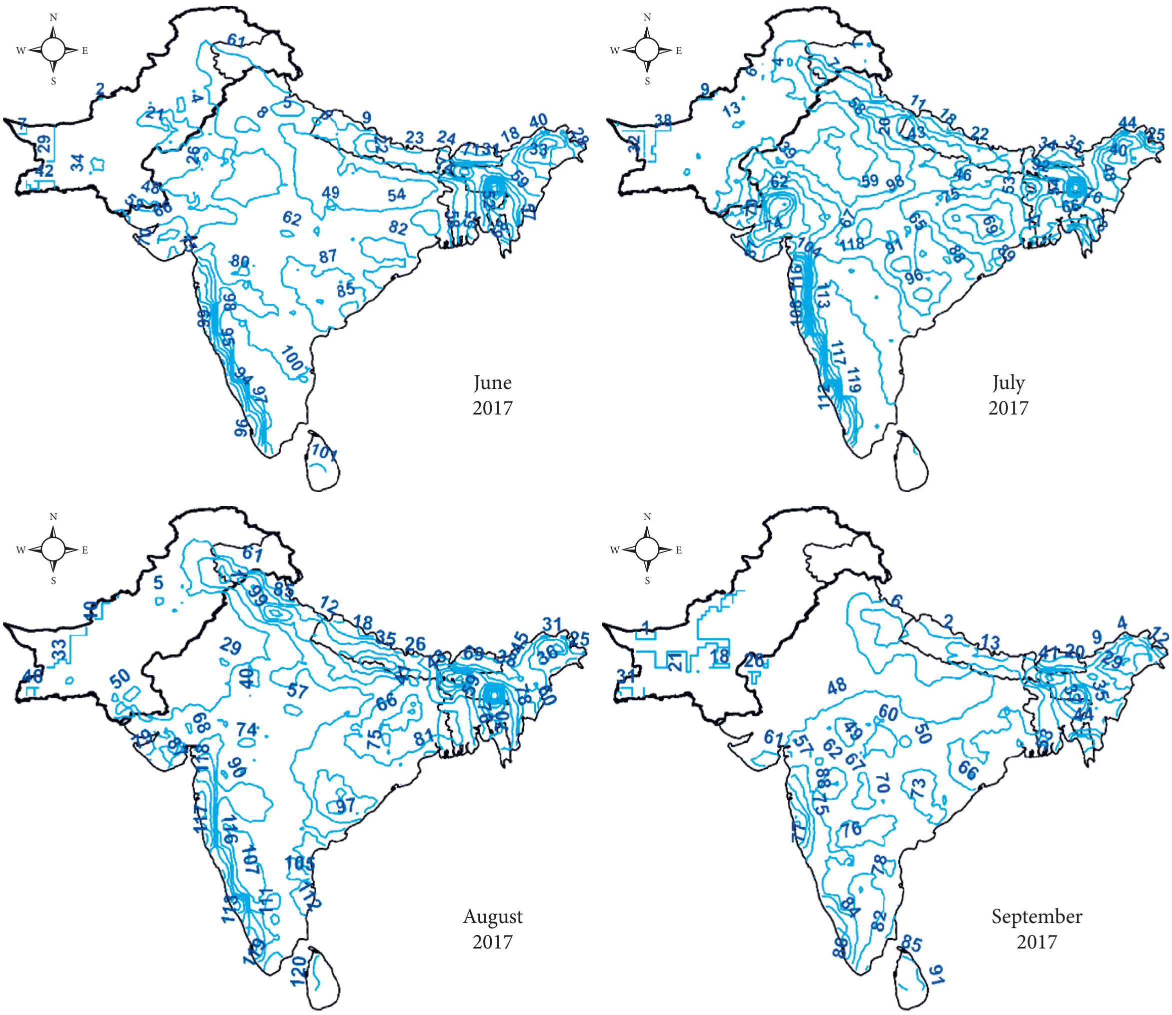


Figure 2: Map of monsoon region over the Indian subcontinent depicting isohyets for the year 2017. Monsoon rainfall depicting the active monsoon period over Pakistan: month of June has a small spread of monsoon rainfall in Pakistan, while July and August are the months with widespread rainfall in Pakistan.

the monsoon and postmonsoon seasons in Pakistan over a period of 38 years (1980–2017). The months of June, July, August, and September constitute the monsoon while October and November constitute the postmonsoon season in Pakistan [18].

Satellite data have been employed to correlate the findings with ground data as well as to observe the shift in monsoon patterns over the study region. The gridded rainfall data for the study have been obtained from Tropical Rainfall Measuring Mission (TRMM). Tropical Rainfall Measuring Mission (TRMM: http://trmm.gsfc.nasa.gov), launched in 1997, used both active and passive microwave instruments to improve rainfall estimates in the tropics and provides a foundation for merging rainfall information from other satellites [22].

The dataset used in this study is TRMM_3B43, which is monthly product with resolution of 0.25 degree × 0.25 degree. The data and further description about the data products can be accessed at https://giovanni.gsfc.nasa.gov.

Rainfall and temperature data from Pakistan Meteorological Department's (PMD) 15 ground stations located in the northern monsoon belt of Pakistan have been used to find the rainfall variability over Northern Pakistan (Figure 1) through long-term and decadal trends analysis. These data have been compared with TRMM observations. Furthermore, the Mann-Kendall test has been employed to check the statistical significance of trends for monsoon rainfall and temperature [23] while Sen's slope estimator has been employed to measure the magnitude of the slope [24]. Spatial shift in monsoon pattern has been analysed using satellite and ground datasets and ArcGIS software version 10.5.1.

Special emphasis has been made on last 8 years from 2010 to 2017 as they include anomalous historical flood year of 2010 and the following recent years. Annual rainfall variability has been calculated using 1980–2009 as the 30-year baseline. Its statistical significance has been checked using one sample mean comparison *t*-test. For TRMM, wherever applicable, the baseline has been set as 1998–2009, since TRMM was launched in 1997, while the observation span remains the same as PMD, i.e., 2010–2017.

3. Results and Discussion

3.1. Comparison of Satellite and Ground-based Observations of Rainfall. Figure 3 shows comparison of monsoon rainfall over Pakistan using TRMM_3B43 satellite dataset and rainfall observed at respective PMD's ground based network within northern monsoon belt. Maps depict baseline (from 1998 to 2009—averaged values of 12 years) and individual years 2010–2017 and their correlation values for the monsoon season (mm/day). For correlation purpose, satellite seasonal mean monsoon values (in mm/day) were extracted for the coordinates of ground stations only. The ground stations are shown as small circles on the maps with the same legend (and colour) values as the satellite data to depict how closely the two datasets correlate with each other. For years 2010 to 2017, seasonal averages of monsoon were plotted. It is evident from figure that both the datasets are strongly correlated with r (Pearson value) ranging from 0.86–0.97. It can be concluded that TRMM satellite data are a useful source and can be used to evaluate rainfall estimates for monsoon season over Pakistan with sufficient accuracy. They can be a valuable source to identify spatiotemporal variability in rainfall over large regions of the Earth's surface where measuring instruments like rain gauges are unavailable [25]. Similar comparison between gridded satellite data (TRMM's datasets 3B42-V6 and 3B42-V7, which are three hourly datasets) and reanalysis products over the Indian subcontinent including Pakistan showed that satellite-derived precipitation product 3B42 (V6 and V7) exhibited strong correlation not only for the monsoon season but also for other seasons as well [26]. A recent study states that TMPA (TRMM Multisatellite Precipitation Analysis) is a reliable substitute of ground data for weather forecasting, water resource management, and crop monitoring in plain as well as medium elevation areas of Pakistan for all four seasons [25].

3.2. Temporal Evaluation of Rainfall and Temperature Variations. Northern monsoon belt of Pakistan receives more than 80% of the total rainfall in Pakistan [18]. It can be clearly seen in Figure 2 that Pakistan receives less rainfall and monsoon depart earlier as compared to the eastern parts of the Indian subcontinent. A comparison of total rainfall and temperature records of northern monsoon belt is presented in Figure 4(a) during monsoon and Figure 4(b) during postmonsoon seasons. Linear fit was employed to both seasonal mean temperature and rainfall records in order to explore any existing trends in both datasets. Monsoon precipitation shows a statistically insignificant decrease of 0.10 mm per, as shown by p value of the Man-Kendall test (Table 1). The long-term temperature data show a statistically significant increase of 0.014°C and 0.026°C per year in the monsoon and postmonsoon seasons, respectively.

Rainfall and temperature records were further investigated in order to explore the observed changes on decadal scales. Since the floods of 2010 constitute a major meteorological and environmental event, it is important to study the trends after that event. Special emphasis has been made on 2010–2017 variations to study changes in recent years.

The first decade of the study 1980–1989 had an increasing rainfall but the following two decades and the last eight years depicted a decreasing monsoonal rainfall, the decrease being the most noticeable in the 2010–2017 (Figure 5). While in postmonsoon, an increasing slope in temperature, i.e., 0.11°C per year, as compared to the baseline is observed (Figure 6). The rise in rainfall through all the decades depicts a uniform increasing (warming) pattern in the study area. Table 2 gives a summary of the decadal variations of monsoon and postmonsoon seasons. Temperature has increased in both monsoon and postmonsoon seasons with the exception of 2000–2009 decade where temperature had a decreasing slope in both seasons. The increase in temperature is quite pronounced during 2010–2017 with 0.18°C and 0.19°C increase in monsoon and postmonsoon, respectively. Haider et al. [14] observed a rise of 0.7°C during 1997–2010 using meteorological stations all over Pakistan.

Precipitation patterns in the tropics and subtropics are controlled by fluctuations in sea-surface temperatures [27], and the strength of linear relationship between ENSO and Indian summer monsoon rainfall has shown deviations on a decadal period, which might either be attributed to teleconnections or natural variations at play. Years which have warm Pacific SST anomalies (El Niño) depict a weak monsoon circulation and a late arrival while a contrary behaviour is observed for years which have La Nina or cold Pacific SST anomalies [28]. This long-acknowledged inverse correlation between ENSO and Indian monsoon precipitation has somewhat declined since the late 1970s, where a drier monsoon and warm event determined by tropical east Pacific sea-surface temperature (SST) anomalies were linked [29]. The decreased rainfall activity is attributed to the decrease of the north-south SST gradient over North Indian Ocean and also the monsoon circulation over India and neighbouring countries [30]. Besides this, significant differences between warming trends over the ocean basins and the Indian land mass may result in a reduced land-ocean temperature contrast and weakening of the strength of organized convergence over India—Indian Ocean Dipole [12–31]. Thus, even if the average trend in sea-surface temperature over the Indian ocean is positive, the spatial distribution of trends does not encourage spatially coherent warm sea-surface temperature (SST) or the organized dynamics necessary for the monsoon [32]. It is further complicated by the changes in land use and land cover [33] and increase or decrease in irrigated land in India which can have local as well as remote effects by altering circulations [34] and increasing concentration of greenhouse gases [2–4].

Since 2010–2017 years show a substantially large decrease in rainfall, an attempt was made to compare the long-term trend of 1980–2009 with the average of the last 8 years to see if the trend remains the same or increases/decreases

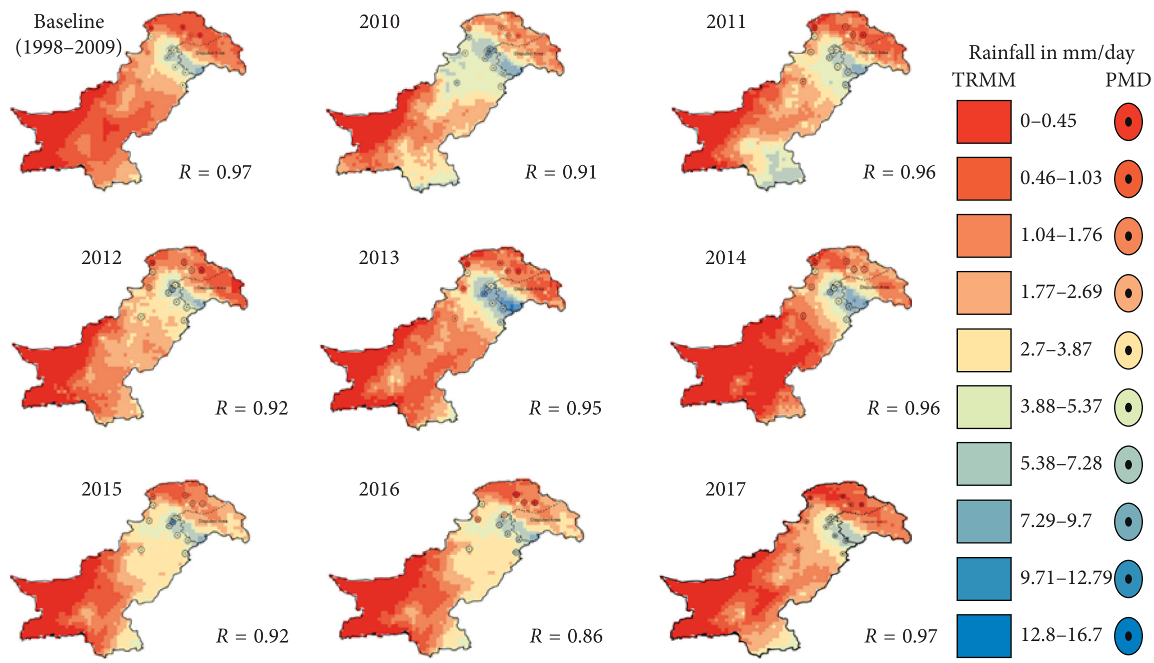


Figure 3: Maps showing rainfall over Pakistan. Correlation between PMD and TRMM_3B43 for seasonal averaged values over selected northern monsoon belt of Pakistan for monsoon season is also listed for respective year. Both the datasets are strongly correlated with Pearson's correlation "r" values ranging from 0.86 to 0.97.

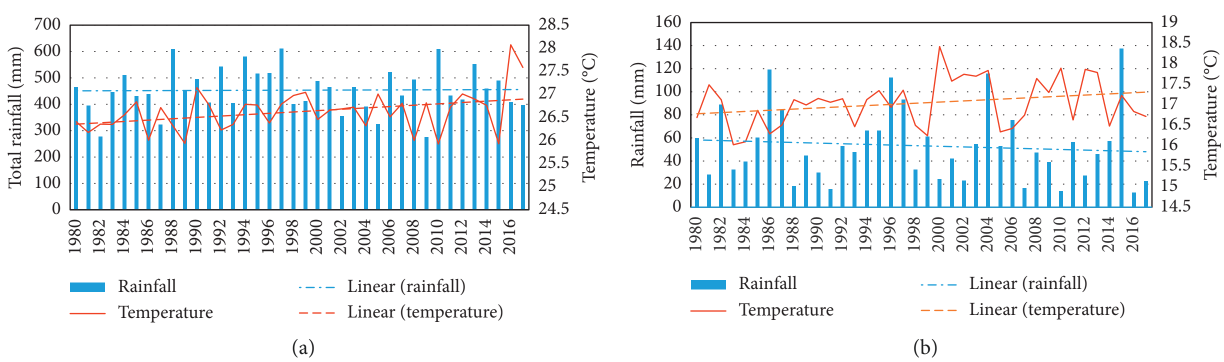


Figure 4: Seasonal mean temperature and rainfall records of northern monsoon region of Pakistan during the time period of 1980–2017 (a) for monsoon months of June, July, August, and September and (b) for postmonsoon months of October and November.

Table 1: Man-Kendall test and Sen's slope values for temperature and rainfall data.

	Alpha	p value	Sen's slope value
Temperature			
Monsoon (1980–2017)	0.05	**0.03**	**0.014**
Postmonsoon (1980–2017)	0.05	**0.0088**	**0.026**
Rainfall			
Monsoon (1980–2017)	0.05	0.94	−0.10
Postmonsoon (1980–2017)	0.05	0.33	−0.39

Bold values show significant values at alpha = 0.05.

(Figure 7). Addition of 2010–2017 average rainfall to the long-term trend did not alter the trend line significantly. The trend of a decreasing rainfall remains the same although 2010 saw an abnormally high monsoon rainfall over Pakistan.

Interannual variability is an important characteristic of the summer monsoon across South Asia. Especially, there exists a large interannual rainfall variability in Pakistan. To highlight this characteristic of the Indian monsoon system, an attempt has been made to study the increase or decrease in mean rainfall for each year from 2010 to 2017. An increase of 26.4, 3.46, 18.99, 2.60, and 8.75 percent in the years 2010, 2011, 2013, 2014, and 2015 was observed, whereas a decrease of 7.43, 9.53, and 11.38 percent was observed in 2012, 2016, and 2017, respectively (Table 3). Due to vast differences in annual rainfall, it is hard to find a monotonic trend in the data. There is a need for continuous monitoring and analysis to evaluate this trend by taking into account the large-scale circulations as well.

The complexity of variations in the South Asian summer monsoon had been demonstrated in recent observations by Turner and Annamalai [19] where a study of 306 stations

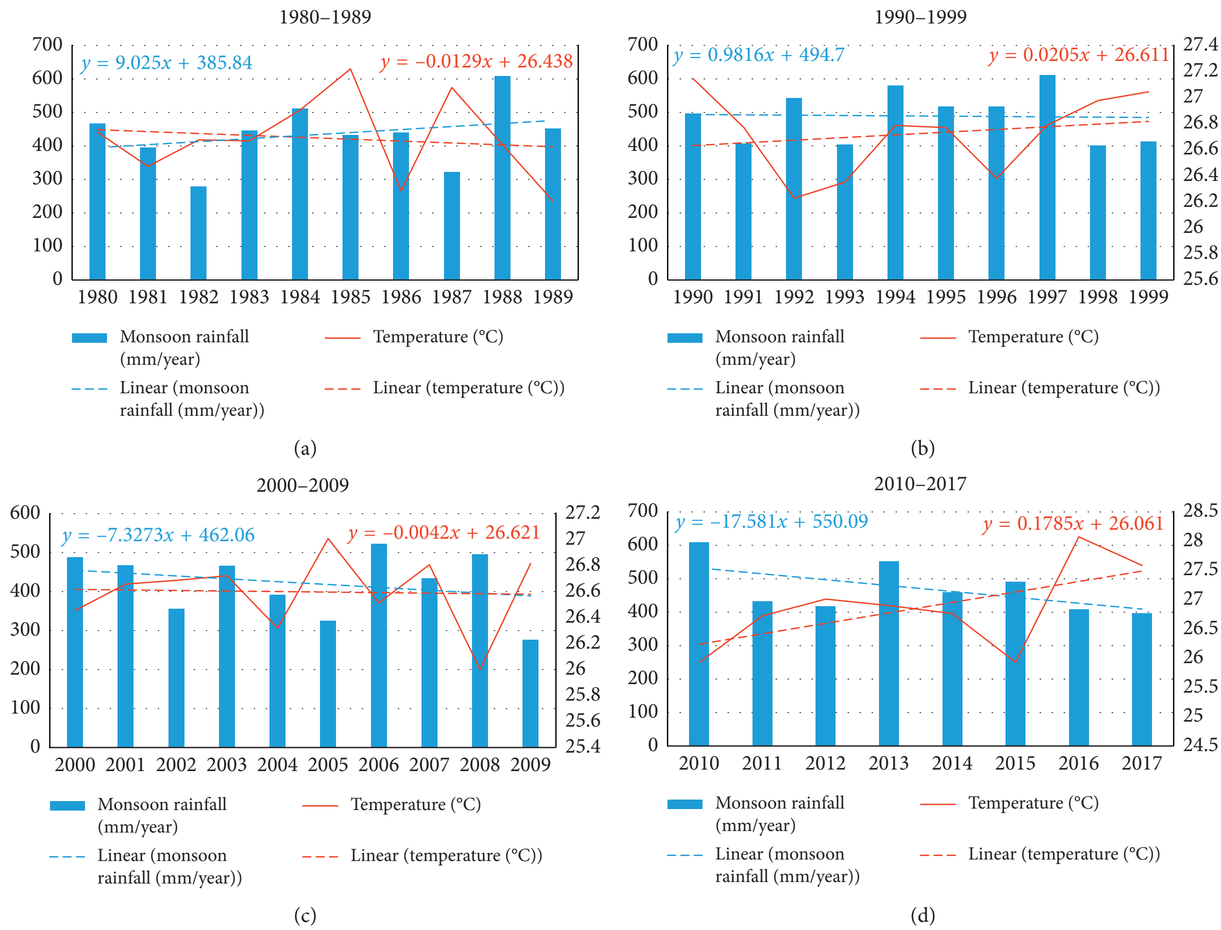


FIGURE 5: Decadal variations of total rainfall and seasonal mean temperature during monsoon season in Pakistan; all the time series after 1990 have shown a decrease in monsoon precipitation, the decrease being the sharpest in the last eight years. Increase in temperature is steepest in the last 8 years as well while 1980–1989 and 2000–2009 showed a slight decrease in temperature.

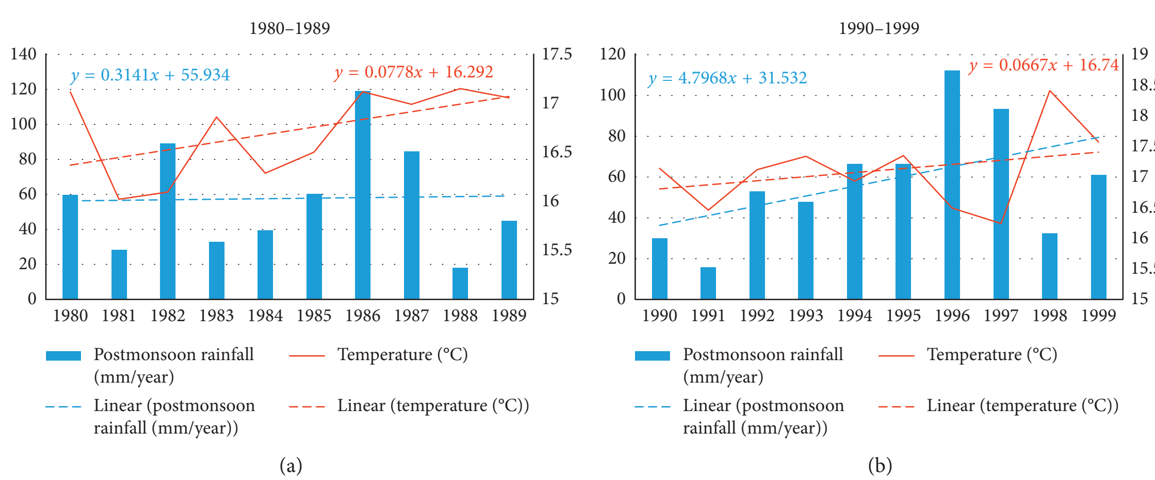


FIGURE 6: Continued.

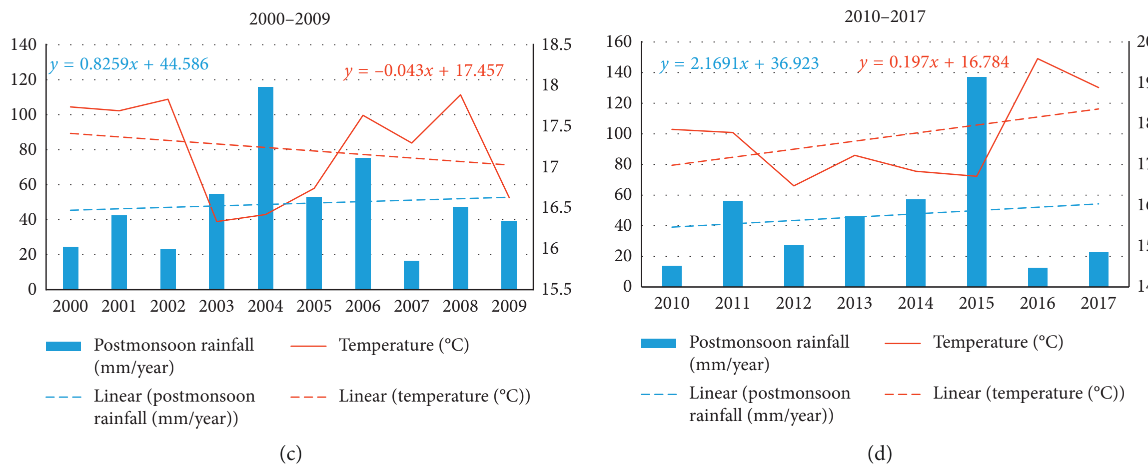


Figure 6: Decadal variations of total rainfall and seasonal mean temperature during postmonsoon season in Pakistan; all decades depict an increase in the postmonsoon rainfall and an increase in temperature except 2000–2009 where a slight decrease in temperature is observed.

Table 2: Decadal changes in monsoon rainfall and seasonal mean temperature in northern monsoon belt of Pakistan during the time period of 1980–2017.

	Decade	Minimum value (year)	Maximum value (year)	Slope magnitude (per decade)
Monsoon rainfall (mm)	1980–1989	278.64 (1982)	608.61 (1988)	9.02
	1990–1999	401.88 (1998)	611.73 (1997)	−0.98
	2000–2009	276.40 (2009)	521.73 (2006)	−7.33
	2010–2017	397.00 (2017)	609.16 (2010)	−17.58
Monsoon temperature (°C)	1980–1989	25.94 (1985)	26.84 (1989)	−0.01
	1990–1999	26.23 (1990)	27.15 (1992)	0.02
	2000–2009	26.00 (2008)	27.01 (2005)	−0.004
	2010–2017	25.93 (2010)	28.07 (2016)	0.18
Postmonsoon rainfall (mm)	1980–1989	18.09 (1988)	119.21 (1986)	0.31
	1990–1999	15.79 (1991)	112.35 (1996)	4.79
	2000–2009	16.57 (2007)	115.88 (2004)	0.83
	2010–2017	12.52 (2012)	137.21 (2015)	2.17
Postmonsoon temperature (°C)	1980–1989	16.02 (1981)	17.15 (1988)	0.08
	1990–1999	16.24 (1997)	18.41 (1998)	0.07
	2000–2009	16.33 (2003)	17.89 (2008)	−0.04
	2010–2017	16.48 (2012)	19.59 (2016)	0.19

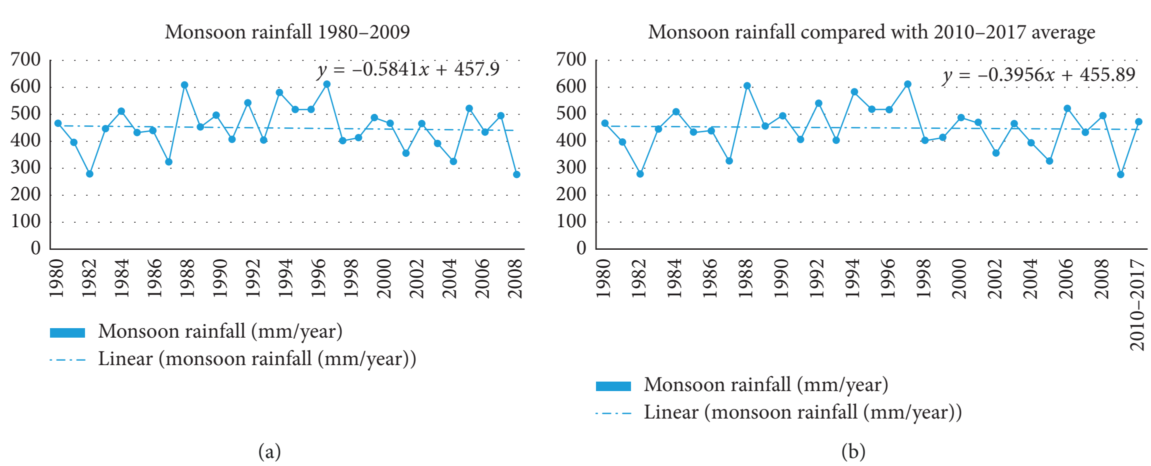


Figure 7: Long-term trend (1980–2009) for monsoon rainfall versus the long-term trend with the average of last 8 years (2010–2017). Both trends depict a decreasing trend in the monsoon rainfall, although 2010 was a year with anomalous high monsoon rainfall.

Table 3: Variability of monsoon rainfall from baseline (1980–2009).

Time	Rainfall-TRMM (mm/day)	Rainfall-PMD (mm/day)	Total rainfall in monsoon-PMD (mm/season)	Absolute change from baseline (mm/season)	Relative change (%)	p value
Baseline (1980–2009)	3.30	3.44	448	—	—	—
2010	4.75	4.99	609	161	26.44	**0.00**
2011	3.62	3.55	433	−15	−3.46	0.31
2012	3.53	3.42	417	−31	−7.43	**0.05**
2013	4.76	4.53	553	105	18.99	**0.00**
2014	3.78	3.77	460	12	2.60	0.49
2015	3.69	4.02	491	43	8.75	**0.01**
2016	3.19	3.35	409	−39	−9.53	**0.02**
2017	3.03	3.25	397	−51	−11.38	**0.002**

One sample t-test was employed to check the significance of the variability of each year. The significant values (<0.05) are highlighted.

over the region demonstrated a negative trend in precipitation but the addition of more recent data to the time series indicates a slightly weaker decrease since 1950 than in a former study, where summer rainfall declined till 2000. The high interannual variability in monsoon can be attributed to ENSO and Indian Ocean Dipole (e.g., [35]) among many other factors. Sea-surface temperatures (SSTs) are the major predictable components of Indian monsoon variability, of which ENSO and IOD are the main drivers.

However, various other factors have been identified which cannot be neglected for their role in rainfall variability. These also include springtime snow depth in the Himalayas, and the presence of aerosols over the region [27, 36]) has been observed to cause a decrease in the Asian summer monsoon rainfall [37].

3.3. Rainy Days in Monsoon and Postmonsoon. Total rainy days in both seasons were calculated to investigate the variability of rainy days on a decadal scale. PMD and Indian Meteorological Department identify a day with 2.5 mm or more rainfall as a rainy day [38]. A day with rainfall equal to or more than 2.5 mm/day was counted as a rainy day for a particular ground station. Total number of rainy days in this study corresponds to the average of rainy days for all ground stations located in the northern monsoon region of Pakistan.

Figures 8 and 9 demonstrate the variations in rainy days during the monsoon and postmonsoon season, respectively. All the decades depict an increase or decrease in the number of rainy days in conformation with the increase and decrease in the total rainfall of the season. A decrease in number of rainy days during monsoon may be linked to more intense rains and more flash floods being reported in Pakistan [7, 39], but this needs to be investigated on a larger time scale. A similar study over Pakistan found decreasing frequency of monsoon rainfall events in northern Pakistan and Gilgit Baltistan [40]. Similarly, Das et al. [32] found a decreasing trend in the mean summer monsoon rainfall and rainy days in Central India and on the western coast.

3.4. Asian Monsoon and Large-Scale Circulations. To study the impact of ENSO on monsoon rainfall variability in Pakistan, an attempt has been made to compare the rainfall pattern with the El Nino and La Nina indices for respective years. Percentage departure of seasonal rainfall from long-term average (1980–2017) has been calculated and plotted in Figure 10. To study how rainfall is impacted by ENSO, El Nino years are classified by red bars while La Nina years are distinguished by green bars.

Record of the El Nino and La Nina years has been taken from Golden Gate Weather Services, Canada (http://ggweather.com/enso/oni.htm), from which the ENSO years falling in our study span are plotted. Only moderate to strong ENSO events are plotted on the graph. It is observed that out of seven El Nino years, five years show a negative departure from the mean while out of six La Nina events, three years have a positive departure from the mean. The years 1994 and 1997 with El Nino depict a large increase in rainfall compared to mean while most of El Nino years show a suppressed monsoon. Various studies have reported decrease in rainfall in Pakistan during El Nino years and increase during La Nina episodes during 1951–2012 [41]. ENSO events affect the Indian monsoon system on large subcontinent scale [42], and the impacts on a small geographical location like Pakistan might not be very evident. A comparative analysis of long-term monsoon precipitation data of ENSO neutral and nonneutral years demonstrated that the seasonal rainfall of Pakistan is impacted by ENSO cycle somewhat, but no significant relationship has been found so far [43].

Indian Ocean Dipole (IOD) represents anomalous behaviour of sea-surface temperatures as to western Indian Ocean becoming alternately warmer and then colder than the eastern part of the ocean [31]. Linkage between SST and winds reveal a strong coupling of ocean dynamics and precipitation patterns. Discrepancy found in correlation of El Nino and increase in monsoon rainfall can be partially addressed by the IOD, as positive IOD index often negates the effect of ENSO, resulting in increased monsoon rains in years such as 1983, 1994, and 1997. However, several studies have stated both positive and negative IOD have consequent impacts on monsoon rains in the Indian subcontinent, Australia, eastern Africa, and Southeast Asian region (e.g. [31, 44]).

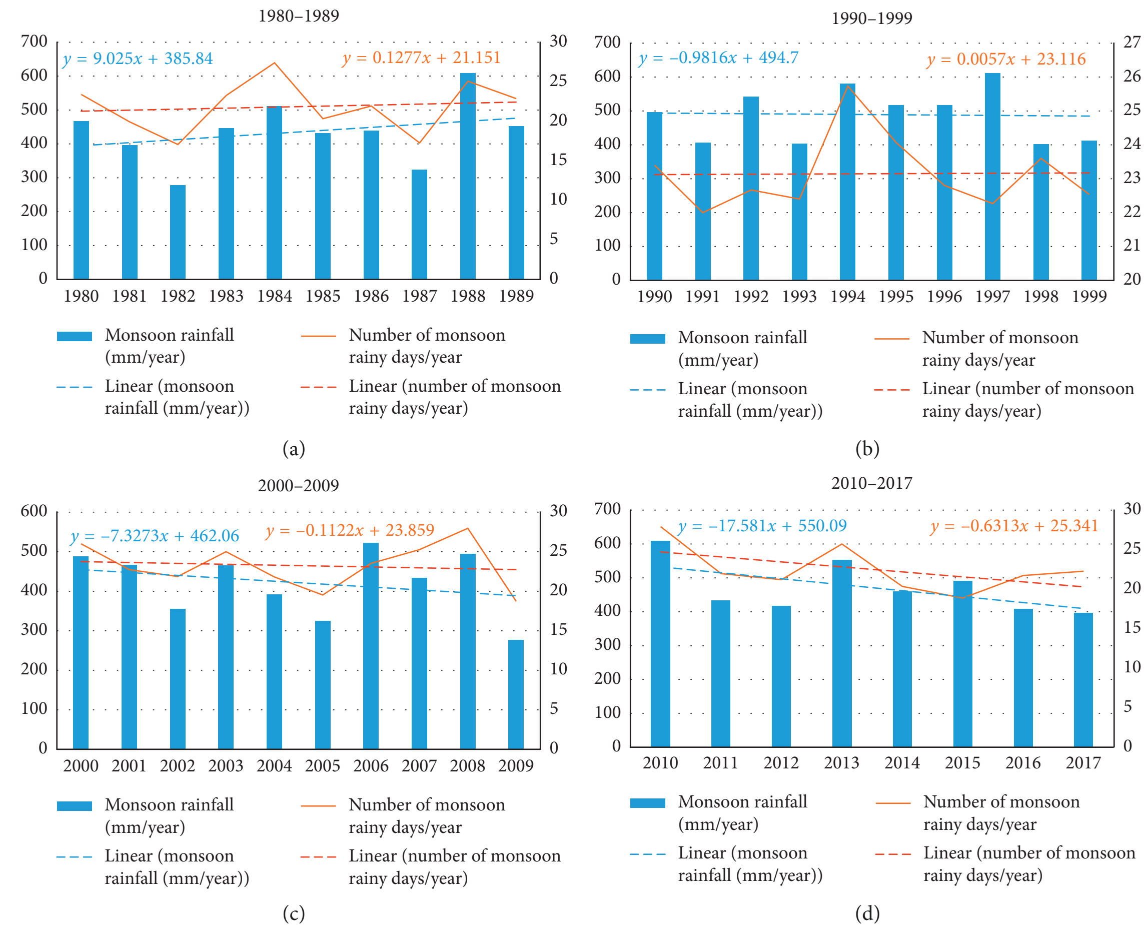


FIGURE 8: Decadal variation in number of rainy days for the monsoon season over Pakistan; the last two decades depict a decrease in the rainy days and monsoon rainfall in the study region.

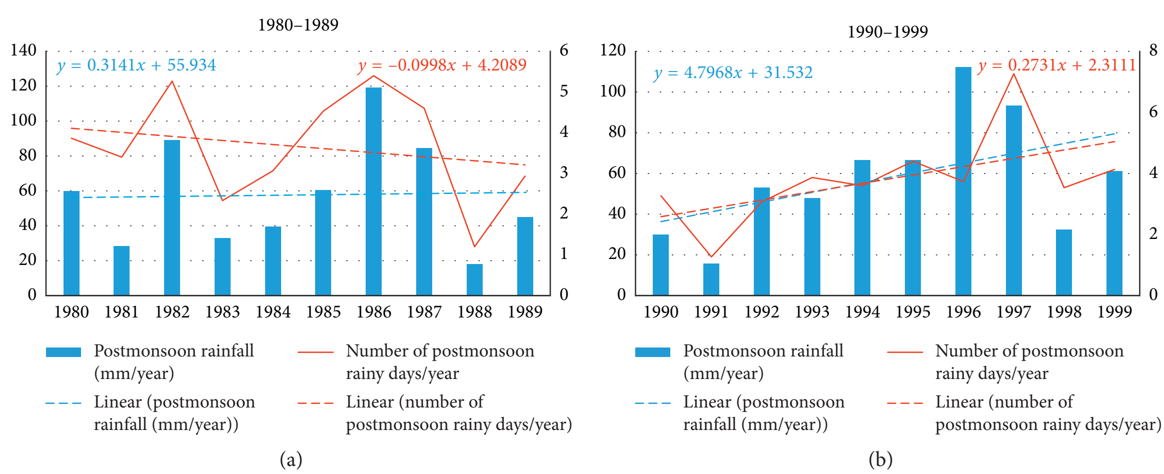


FIGURE 9: Continued.

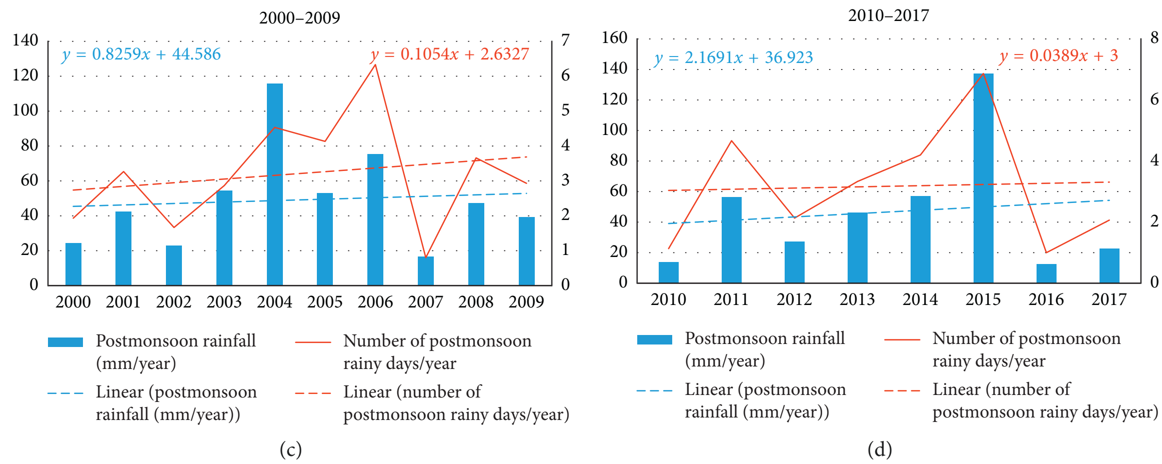


Figure 9: The number of rainy days during postmonsoon depicts an increase in almost all decades.

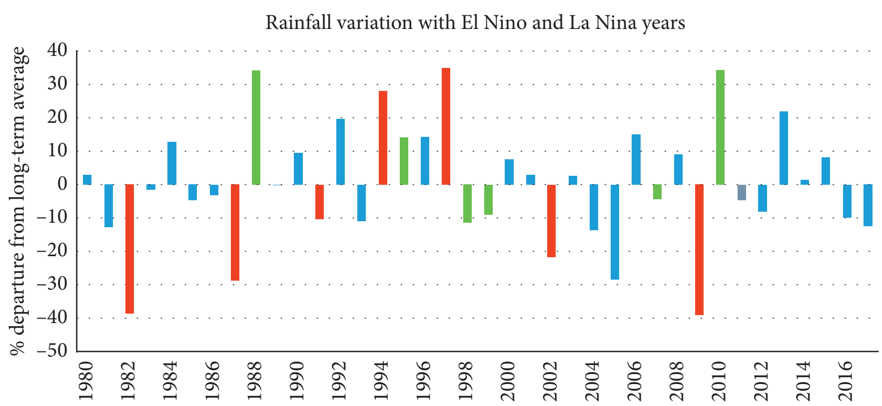


Figure 10: Impact of El Nino and La Nina years on monsoon variability in Pakistan. Red bars show the rainfall departure from long-term mean for El Nino years while green shows the same for La Nina and blue for neutral years.

Besides IOD, ENSO does impact monsoon rainfall variability in Pakistan and other regions to some extent, but it is not a sole factor and not strongly correlated as well.

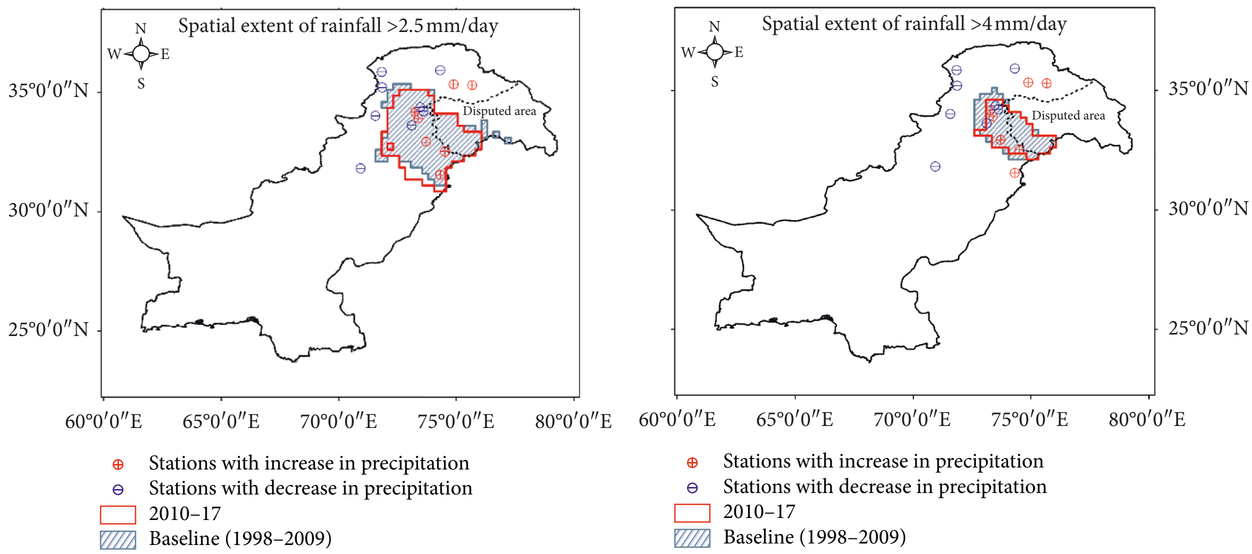
3.5. Spatial Shift in Monsoon Patterns. Changing climate is also manifesting itself as spatial shifts in precipitation patterns in various parts of the world. One of the most susceptible of these changes is the spatiotemporal shift in the Indian monsoon system. To investigate if there is a spatial shift in monsoon precipitation occurrence over Pakistan during the time period of 2010–2017 with respect to a baseline of 1998–2017, rainfall extent was calculated using ArcGIS software version 10.5.1 at two threshold values, i.e., rainfall more than or equal to 2.5 mm per day and greater than 4 mm per day. According to PMD, 2.5 mm/day is the minimum amount of rain a day can be identified as a rainy day, while 4 mm/day threshold has been taken to depict a medium to high intensity rainfall events. This shift was calculated using TRMM satellite data by selecting only those pixels that had rainfall values greater than the threshold values. Since these data (TRMM_3B43) are monthly rainfall product, we used averaged daily values of 2.5 mm/day and 4 mm/day as our threshold values.

These pixels created a distinct polygon (different colour represent respective years in Figure 10) which was the area with monsoon precipitation above rainfall threshold value per day. The area affected by monsoon for each year is calculated, and averaged area is calculated for the baseline (1998–2009) as well as the study years 2010–2017.

Ground station data from PMD were also analysed for decreasing and increasing trends over the ground stations, and stations were plotted on top of the satellite data spatial extent and shift. The stations exhibiting increasing rainfall are shown by red marks and plus sign while station with decreasing rainfall are shown by blue dots and negative signs in Figure 11.

Spatial extent of monsoon rainfall varies greatly each year as shown in Figure 12; the average spatial extent for rainfall greater than 2.5 mm/day seems to extend southeastwards from the 1998–2009 average extent.

A decrease in area affected by monsoon for 4 mm/day rainfall threshold (moderate to heavy rainfall) and an increase in 2.5 mm/day threshold are identified (Table 4).



(a) (b)

Figure 11: Spatial Shift of monsoon in northern monsoon belt of Pakistan. There is an increase in monsoon hit area with rainfall ≥2.5 mm/day of 56033 km^2 and a decrease of 25,261 km^2 in area with rainfall ≥4 mm/day. A shift towards south-east and east can be observed in respective scenarios.

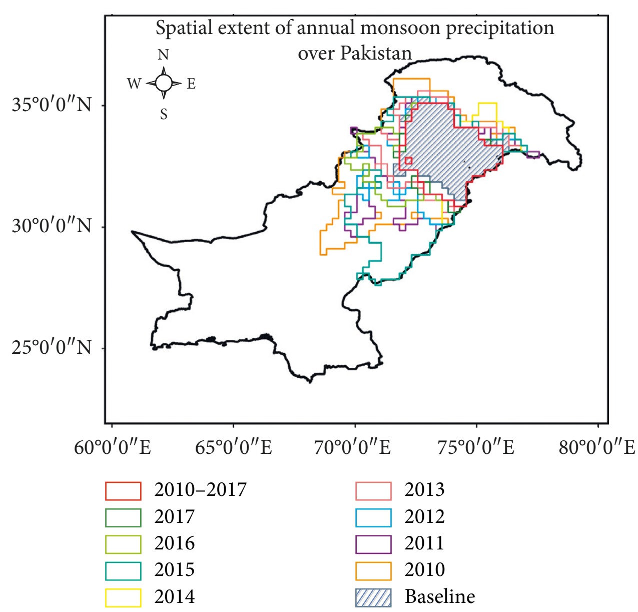


Figure 12: Annual spatial extent of monsoon rainfall in northern monsoon belt of Pakistan. Each colour shows the extent of monsoon rainfall over Pakistan for the respective year.

Decrease in sufficient monsoon rainfall affected area might have negative consequences such as water management for agricultural and other purposes. Considering the region in Figure 11 that received 2.5 mm/day rainfall during monsoon, there is a south-eastern shift of 11752 km^2 on lower end (advancing side), while a 7523 km^2 shift from the upper end (receding side) of the northern monsoon belt. There is a westward shift of 14388 km^2 in rainfall region with rainfall above 4 mm/day (receding side).

Spatial shift in monsoon patterns inferred from TRMM data is also confirmed by the observations from PMD stations. As depicted is Figure 11, majority of the stations located at the south-eastern side of the study area exhibited an increase in rainfall while a decreasing trend in the north-western side of the northern monsoon belt of Pakistan was observed.

Hanif et al. [43] identified a westward shift in monsoon patterns during the time period of 1951–2010 by using ground stations data only. Further, it might be largely influenced by the anomalous heavy rainfall in north-western parts of monsoon belt during the year 2010. The present study focuses on spatial shift from year 2010 and onwards

Table 4: Extent of spatial shift of monsoon over northern monsoon belt of Pakistan for different thresholds of rainy and moderate to heavy rainfall.

Year	Area (km^2)	Difference from baseline area (km^2)	Average area (2010–2017) (km^2)	Difference (km^2)	Shift (km^2)	
					Advancing side	Receding side
≥2.5 mm/day (light rainfall)						
Baseline (1998–2017)	**225,322**		**281,355**	**+56,033**	**11,752**	**7,523**
2010	441,384	216,062				
2011	270,487	45,165				
2012	269,659	44,337				
2013	236,788	11,466				
2014	203,541	−21,781				
2015	420,155	194,833				
2016	243,272	17,950				
2017	165,551	−59,771				
≥4 mm/day (moderate to heavy rainfall)						
Baseline (1998–2017)	**158,838**		**133,567**	**−25,271**		**14,388**
2010	292,311	133,473				
2011	153,214	−5,624				
2012	85,961	−72,877				
2013	137,429	−21,409				
2014	116,010	−42,828				
2015	110,730	−48,108				
2016	92,809	−66,029				
2017	80,073	−78,765				

and employed satellite data to calculate the area in km^2 of spatial shift. Furthermore, the extent of the shift has not been calculated in published literature over the area so far.

4. Conclusions

The rainfall and temperature variability investigated in this study is a part of the longer climatic trends of the area. It exhibited a tendency towards a warming and weakening monsoon over the northern monsoon belt of Pakistan, particularly during the last 8 years. A more pronounced decrease is observed in monsoon rainfall during 2010–2017 as compared to the previous three decades, signifying a recent drier monsoon over the region after the anomalous heavy rains of 2010. Over the study area, there is 0.01°C per year rise in monsoon temperature along with a 0.1 mm per year decrease in rainfall while the rise in temperature during the last eight years of the study, i.e., 2010–2017, is more pronounced (0.18°C and 17.58 mm/year decrease in rainfall). Comparison of TRMM and PMD datasets exhibited a significant correlation with each for rainfall over 15 stations in the northern monsoon belt of Pakistan. Pearson's value ranged from 0.86 to 0.97.

Results have shown a spatial shift in the monsoon rainfall in Pakistan. There is a southward spatial shift in monsoon rainfall occurrence over Pakistan while an eastward shift in moderate to heavy monsoon rainfall events.

Interannual variability is an important characteristic of monsoon in Pakistan which makes it hard to predict a certain trend in rainfall pattern. Monsoonal variability and inconsistency can be partially attributed to large-scale circulations such as IOD and ENSO. However, there is strong need to corroborate additional factors such as evolution of greenhouse gases, observed warming, role of aerosols, and land use and land cover changes in the region.

Data Availability

The satellite data used to support the findings of this study are available at https://giovanni.gsfc.nasa.gov. The ground station's data used to support the findings of this study were supplied by the Pakistan Meteorological Department (PMD) under license and so cannot be made freely available. Requests for access to these data should be made to the Computerized Data Processing Center (CDPC) of Pakistan Meteorological Department (PMD) at info.cdpc@pmd.gov.pk.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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