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Spatial distribution of secular trends in annual and seasonal precipitation over Pakistan

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ABSTRACT: The presence of autocorrelation and long-term persistence (LTP) can lead to considerable change in the significance of trends in hydro-climatic time series. This therefore casts doubt on past findings of climatic trend studies that did not consider LTP. We assessed the trends in spatiotemporal patterns of annual and seasonal precipitation of Pakistan in recent years (1961–2010) using precipitation data from the Global Precipitation Climatology Centre (GPCC) using (1) the ordinary Mann-Kendall (MK) test and (2) the modified Mann-Kendall (MMK) test, which can discriminate LTP from unidirectional trends. The results indicate that significance in trends obtained using the MK test is reduced when LTP is taken into consideration. The annual precipitation in Pakistan is increasing in the northern highlands and a few places in the sub-Himalayan ranges in northeast Pakistan, where monsoon precipitation is also increasing. There is no indication of significant change in winter precipitation. Post-monsoon precipitation is increasing at a few locations in the monsoon-dominated southeast region and decreasing in the southwestern arid region.

KEY WORDS: Long-term persistence · Precipitation trend analysis · Modified Mann-Kendall · GPCC data · Pakistan

1. INTRODUCTION

Changes in precipitation often eventually lead to floods or droughts, affecting agricultural productivity, economic activities, the ecological environment and human wellbeing (Akinsanola & Ogunjobi 2017). Therefore, precipitation trend analysis has been of great concern and has been an important issue in the past decades. Studies have demonstrated that global annual mean precipitation over land has increased in the range of 1.01–2.77 mm per decade over the 20th century (IPCC 2013); however, there is a lack of data at a regional scale. Therefore, different studies have been conducted to understand the trends of climate at regional scales, such as in the Korean peninsula (Sung et al. 2017), Sicily (Liuzzo et al. 2016), Serbia (Lukovi et al. 2014), Australia (Nicholls & Lavery 1992), the United Kingdom (Osborn & Hulme 2002), Spain (Río et al. 2011), Bangladesh (Shahid 2011), India (Taxak et al. 2014), Sri Lanka (Wickramagamage 2016), Indonesia (Yanto et al. 2016), China (Zhai et al. 2005), Canada (Zhang et al. 2000), and the United States (Bracken et al. 2015).

Pakistan, a developing country, ranked 10th by the Global Climate Risk Index 1994–2013, has frequently been affected by extreme weather events (Kreft et al. 2014). Over 40% of Pakistan is highly prone to natural disasters due to variation in precipitation pat-

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terns (Salma et al. 2012). The climate in most parts of Pakistan is semi-arid and arid (Petr 2003), and the economy of the country is highly dependent on crop agriculture (Kazmi et al. 2015). This has made Pakistan one of the most vulnerable countries in the world to climate change. Recent studies have reported an increase in precipitation by 22.6 and 20.8 mm from 1901 to 2010 in the monsoon and winter seasons, respectively (see GOP 2013). Studies have also reported that precipitation in the region has become very unreliable and unpredictable in recent years (IPCC 2007, Syed et al. 2014). The devastating floods of 2010–2012 and prolonged severe droughts of 1998–2001 are evidence of increased climate variability in the region. These extreme events have influenced water supply, agriculture, power production, etc. (Zhu et al. 2015). Therefore, understanding the changing patterns of precipitation trends are important for reliable assessment of water resource management, drought and flood mitigation plans, and understanding climate change across Pakistan.

A literature review revealed that several studies have been conducted for assessment of precipitation trends across Pakistan using various statistical techniques. Farooqi et al. (2005) analyzed rainfall trends for the period 1951–2000 over different regions using simple linear regression. Cheema et al. (2006) investigated the trends over a station located in Faisalabad for the period 1945–2004 using simple linear regression. Zahid & Rasul (2011) used data from 41 stations to evaluate the trends in extreme precipitation events by considering different percentiles. Salma et al. (2012) used ANOVA along with Dunnett's T3 test to assess the precipitation trends for the period 1976–2005 over different climatic zones. Hartmann & Andresky (2013) used gridded precipitation data to investigate the trends over the Indus basin for the periods 1951–2010 and 1986–2010 using the Mann-Kendall (MK) trend test. Hanif et al. (2013) examined the latitudinal precipitation characteristics using the MK trend test over a 60 yr period using data from 48 rain gauges. Hussain & Lee (2014) studied the precipitation trends using simple linear regression and a Kendall's tau-based test. Ahmad et al. (2015) investigated the monthly, seasonal and annual precipitation trends using MK and Spearman's rho (SR) tests at 15 stations in the Swat river basin over a 50 yr (1961–2011) period. Khattak & Ali (2015) examined the trends over Punjab province using the MK test and Sen's slope techniques after removing serial correlation in data using trend Free Pre-Whitening approach. Ali et al. (2015) assessed precipitation trends using the MK test and Sen's slope estimator using 30 yr (1981–2010) of station-based monthly precipitation data sets. Latif et al. (2017) studied monsoon trends over the whole of Pakistan using simple linear regression, and confirmed their significance using the MK trend test. Even though several studies have investigated precipitation trends over Pakistan, there is still no comprehensive study on trend magnitude, patterns and significance during different climatic seasons such as monsoon (June–September), winter (December–March), pre-monsoon (March–April) and post-monsoon (October–November). Most of the studies on precipitation trend analysis used the standard MK test over 30–50 yr of climate data, with the assumption that natural variability alters the climate pattern on time scales shorter than 30 yr (WMO 1996). Recent analysis of multi-centennial time-series data reveals that wet or dry periods >50 yr can exist (Lacombe et al. 2012). It has been reported that long-term persistence (LTP) or the Hurst phenomenon can inflate the variance of the test statistics and substantially affect the significance of the results obtained under the assumptions of independence and short-term persistence (Hamed 2008). Therefore, a number of recent studies cast doubt on results previously obtained that did not take into account LTP and/or Hurst phenomenon (Kumar et al. 2009, Ehsanzadeh & Adamowski 2010, Shahid et al. 2014, Fathian et al. 2015).

The modified Mann-Kendall (MMK) test is proposed by Hamed (2008) to account for the scaling effect. The MMK test enhanced the ability of the MK test to discriminate multi-scale variability from unidirectional trends. Thus, the MMK test is used in the present study to assess the trends in annual and seasonal precipitation of Pakistan. We compare results with that obtained using the MK test to show how the pattern in precipitation trends changes under the hypothesis of LTP.

2. STUDY AREA AND DATASETS

2.1. Study area

Pakistan occupies an area of 796 100 km^2, and is mainly dominated by arid to semi-arid climate. Geographically, it is located between 23° and 37° N and 61° and 78° E. Pakistan is a land of great topographic contrasts (Fig. 1); therefore, the climate of the country has large spatial and temporal variations. The northern and western mountain ranges in the country add to the wide variation in the climate. Most of the areas of Pakistan are very sensitive to changes in

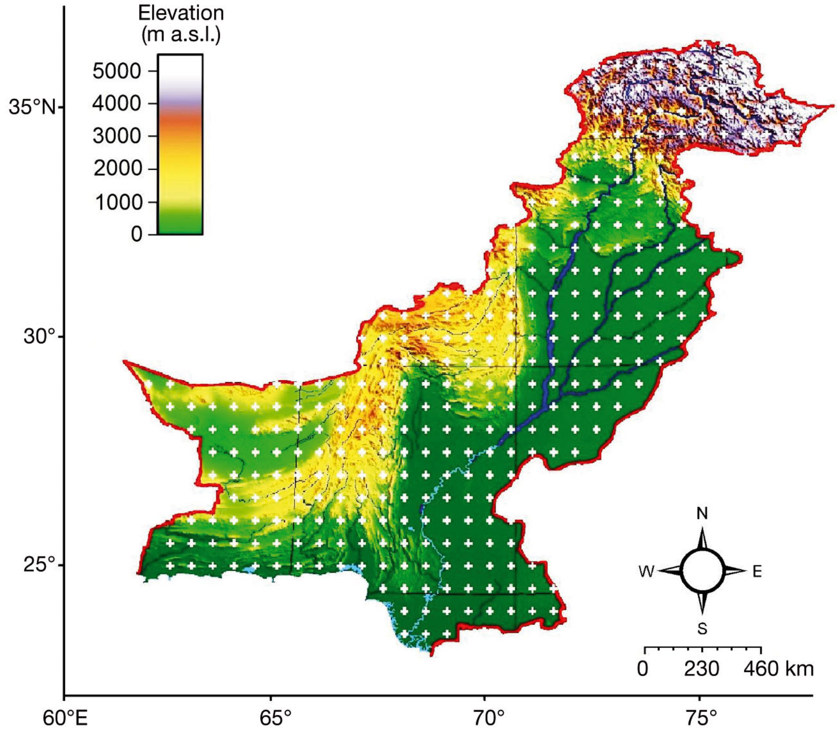

Fig. 1. Topographic map of Pakistan. (+) Global Precipitation Climatology Centre (GPCC) grid

precipitation, and are highly vulnerable to floods, droughts and other natural disasters (Hanif et al. 2013).

The climate of Pakistan can be classified into 4 seasons based on precipitation and temperature: (1) monsoon (June–September); (2) post-monsoon (October–November); (3) winter (December–March); and (4) pre-monsoon (April–May) (Kureshy 1995, Sheikh 2001, Hussain & Lee 2009, Naheed & Rasul 2011, Naheed et al. 2013). The country receives about 58.5% of the annual precipitation during the monsoon season (Salma et al. 2012). The monsoon winds bring moist air from the Bay of Bengal and enter the country from the southeast. As the monsoon progresses over the land, the air moisture content reduces, and the amount of monsoon precipitation gradually decreases from the east to the west. Therefore, the eastern belt of the country receives more precipitation during the monsoon season (Sheikh 2001, Hussain & Lee 2016). The mean monthly temperature during the monsoon season exceeds 35°C in most of the country, with extremes (>50°C) in the south. The pre-monsoon season is characterized by high temperatures in the range of 32 to 53°C and low precipitation in the range of 5 to 130 mm (Iqbal et al. 2016). Thunderstorms bring a small amount of precipitation in this season, and they mostly occur in the eastern part of the country. The post-monsoon season also provides very little precipitation, but the temperature in this season ranges from 18°C to below 5°C. In winter, the temperature reaches below 5°C in some parts of the country, except in the coastal areas, where mild to warm temperatures (20 to 25°C) prevail. The northwest part of the country receives the major portion of total annual precipitation during winter. The western depressions that originate in the Mediterranean Sea travel eastward in the higher latitudes, and the northern regions lying at 34° to 36° N receive the most precipitation due to the topography of the Himalayan Mountains (Snead 1968). These disturbances induce secondary precipitation in the lower latitudes of 25° to 30°N, which extract moisture from the Arabian Sea and bring a small amount of precipitation to the southern part of the country (Hanif et al. 2013).

2.2. Data and sources

The Global Precipitation Climatology Centre (GPCC) has produced several gauge-based gridded precipitation products at different spatial resolutions (Schneider et al. 2014). In the present study, 0.5° spatial resolution Full Data Reanalysis Product Version 6 from GPCC is used. The main advantages of using gauge-based GPCC data are (1) the quality of the dataset is good enough for hydrological analysis; (2) it is a climate model derived dataset, which uses the highest number of observed precipitation records; (3) the time span of the data is long enough for conducting hydrological studies; and (4) the dataset does not have missing data after January 1951 (Spinoni et al. 2014). Studies have reported better performance for the GPCC compared to other products using conventional statistical methods (Prakash et al. 2015, El Kenawy & McCabe 2016, Kishore et al. 2016). In addition to this, GPCC data have been found to have good correlation with observed data from Pakistan (Hartmann & Andresky 2013, Adnan & Ullah 2015, Ahmed et al. 2016). The monthly precipitation dataset from 337 gridded points covering Pakistan over the time period 1961–2010 is used in the present study.

3. METHODOLOGY

In this study, the non-parametric MK test (Kendall 1948) and the MMK test (Hamed 2008) were used to assess the trends, and the non-parametric Sen's slope method (Sen 1968) was used to measure the magnitude of change in precipitation. The MK test is recommended by the World Meteorological Organization (WMO) for analyzing hydrological and meteorological trends (Sneyers 1990). The main advantage of this method is its capability to cope with missing values or outliers. Furthermore, the performance of this method does not depend on the distribution of the data (Sonali & Nagesh Kumar 2013). Adding to the advantages of the MK test, the MMK test can account for the scaling effect, thus enhancing the ability of the test to discriminate multi-scale variability from secular trends (Shahid et al. 2014). In contrast, Sen's slope method gives a robust estimation of the magnitude of linear change (Yue et al. 2002, Mayowa et al. 2015). Some trends may not be detected by statistical tests at a given significance level, but the change might be of practical interest (Basistha et al. 2007). The tests are described in detail below.

3.1. Mann-Kendall trend test

The MK test statistic (S) for precipitation series can be calculated as:

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} Sign\,(x_i - x_j) \tag{1}$$

where n is the length of data series and x_i and x_j are the data points in the time series at i and j:

$$sign(x_i - x_j) = \begin{cases} -1 & for\ (x_i - x_j) < 0 \\ 0 & for\ (x_i - x_j) = 0 \\ 1 & for\ (x_i - x_j) > 0 \end{cases} \tag{2}$$

The probability associated with S and the sample size, n, are then computed to statistically quantify the significance of the trend. The normalized test statistic Z is computed from the variance of S, VAR(S), as follows:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{VAR}(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S-1}{\sqrt{\mathrm{VAR}(S)}} & if\ S < 0 \end{cases} \tag{3}$$

At the 99% significance level, the null hypothesis of no trend is rejected if $|Z| > 2.575$, and at the 95% significance level, the null hypothesis of no trend is rejected if $|Z| > 1.96$.

3.2. Sen's slope method

Sen's slope method calculates the slope (β) as a change in measurement per change in time:

$$\beta = median\left[\frac{x_j - x_i}{j - i}\right] \quad for\ all\ i < j \tag{4}$$

3.3. Modified Mann-Kendall trend test

To assess trends using the MMK test, Sen's slope is first computed for the sample data using Eq. (4) and the trend from the time series x_i is removed to obtain the de-trended series using the following equation:

$$x_i' = x_i - (\beta \times i) \quad for\ i = 1 : n \tag{5}$$

The equivalent normal variants of rank of the de-trended series are obtained using the following equation:

$$Z_i = \phi^{-1}\left(\frac{R_i}{n+1}\right) \quad for\ i = 1 : n \tag{6}$$

where R_i is the rank of the de-trended series x_i', n is the length of the time series and ϕ^{-1} is the inverse standard normal distribution function (mean = 0, standard deviation = 1).

In the next step, the correlation matrix for a given Hurst coefficient (H) is derived using the following equation:

$$C_n(H) = [\rho_{\,|j-i|}] \quad for\ i = 1 : n,\ j = 1 : n \tag{7}$$

$$\rho_l = \frac{1}{2}\left(|l+1|^{2H} - 2|l|^{2H} + |l-1|^{2H}\right) \tag{8}$$

where ρ_l is the autocorrelation function of lag l for a given H, and is independent of the time scale of aggregation for the time series (Koutsoyiannis 2003).

The value of H is obtained by maximizing the log likelihood function of H as given below:

$$LogL(H) = -\frac{1}{2}\ log|C_n(H)| - \frac{Z^T[C_n(H)]^{-1}Z}{2\gamma_0} \tag{9}$$

where $|C_n(H)|$ is the determinant of correlation matrix $[C_n(H)]$, Z^T is the transpose vector of equivalent normal variates Z, $[C_n(H)]^{-1}$ is the inverse matrix and γ_0 is the variance of Z_i. Eq. (9) can be solved numerically for different values of H, and the value for which $LogL(H)$ is maximum is taken as the H-value for the given time series x_i. In this study, the value of H is between 0.50 and 0.98, with an incremental step of 0.01.

The significance level of H is determined by using mean (μ_H) and standard deviation (σ_H) when $H = 0.5$ (normal distribution) as given by the following equations (Hamed 2008):

$$\mu_H = 0.5 - 2.87n^{-0.9067} \tag{10}$$

$$\sigma_n = 0.7765n^{-0.5} - 0.0062 \tag{11}$$

In the present study, the 5% significance level is used for determining significant H. If H is found to be significant, the variance of S is calculated using following equation for a given H:

$$V(S)^{H'} = \sum_{i<j}\sum_{k<l} \frac{2}{\pi} \sin^{-1}\left(\frac{\rho\,|j-i| - \rho\,|i-l| - \rho|j-k| + \rho\,|i-k|}{\sqrt{(2-2\rho\,|i-j|)(2-2\rho\,|k-l|)}}\right) \tag{12}$$

where ρ_l is calculated using Eq. (8) for a given H, and $V(S)^{H'}$ is the biased estimate. The unbiased estimate $V(S)^H$ is calculated by multiplying by a bias-correcting factor B as:

$$V(S)^H = V(S)^{H'} \times B \tag{13}$$

where B is a function of H as below:

$$B = a_0 + a_1H + a_2H^2 + a_3H^3 + a_4H^4 \tag{14}$$

The coefficients a_0, a_1, a_2, a_3 and a_4 in Eq. (14) are functions of the sample size n. These are found in Hamed (2008). The significance of the MMK test is computed using $V(S)^H$ in place of VAR(S) in Eq. (3).

3.4. Spatial analysis of trends

The spatial patterns of annual and seasonal precipitation were mapped using the ordinary kriging method available in ArcGIS 10.3. Kriging is a method widely used for interpolating data to predict unknown values from observed data provided at known locations. A number of estimating methods are available for interpolating point data, including ordinary kriging, universal kriging, co-kriging and others. Ahmed et al. (2014) showed that ordinary kriging with Gaussian and exponential semi-variograms performs better in the study area than other methods available in the kriging family. Therefore, ordinary kriging with Gaussian and exponential semi-variograms were used to map precipitation.

4. RESULTS

4.1. Spatial patterns of annual and seasonal precipitation

The mean annual precipitation over Pakistan for the period 1961–2010 is shown in Fig. 2. Precipitation was equally divided into 10 classes that vary from <100 mm in the northwest to >1000 mm in the northern parts of the country. Precipitation gradually decreases from the north towards the south, and is relatively high in northern areas and low in southern areas. Since Pakistan is mostly characterized by an arid and semi-arid climate, the majority of the country receives precipitation of <500 mm annually, while a very small area receives precipitation of >1000 mm.

The spatial distribution of monsoon precipitation is depicted in Fig. 3a. Precipitation was equally divided into 9 classes that range from <50 to >450 mm. The highest monsoon precipitation occurs in the northeast and southeast parts of the country. In contrast, the lowest precipitation occurs in the western parts of the country. The monsoon of Pakistan flows in 2 branches, i.e. the northeast and southeastern monsoons. The southeastern monsoon brings precipitation from the Arabian Sea and is considerably weaker compared to the northeastern monsoon. The northeastern monsoon brings precipitation mainly from the deflected monsoon currents traveling from the Bay of Bengal along the foothills of Himalayas and enters the northeastern part of the country (Imran et al. 2014). This is evident in Fig. 3a; precipitation is high in northern areas where the monsoon has more influence, whereas it is low in the southeast where it has less influence.

The spatial distribution of winter precipitation is displayed in Fig. 3b. Precipitation was divided into 6 classes that vary from <50 to >300 mm. The map shows the lowest winter precipitation (<50 mm) in southeastern Pakistan and the highest precipitation (>300 mm) in northern Pakistan. Winter rain occurs due to western disturbances originating in the Mediterranean Sea or Atlantic Ocean. These winds lose a lot of moisture during the long travel time and, therefore, bring only a small amount of rain to various parts of Pakistan (Ahmed et al. 2015). Conversely, the western highlands receive more precipitation from the western depressions than any other sources (Khan 1991). Therefore, the winter precipitation map shows higher precipitation in western parts of Pakistan and above 30° N.

Pakistan receives a substantial amount of precipitation during the pre-monsoon season. The southwest monsoon usually retreats from Pakistan in the middle of September. At the same time, severe tropical cyclones are formed in the Bay of Bengal and the Arabian Sea. These cyclones strike the coastal areas and cause intense precipitation (Subramanya 2005). Therefore, precipitation in this season is generally less than monsoon or winter precipitation but highly

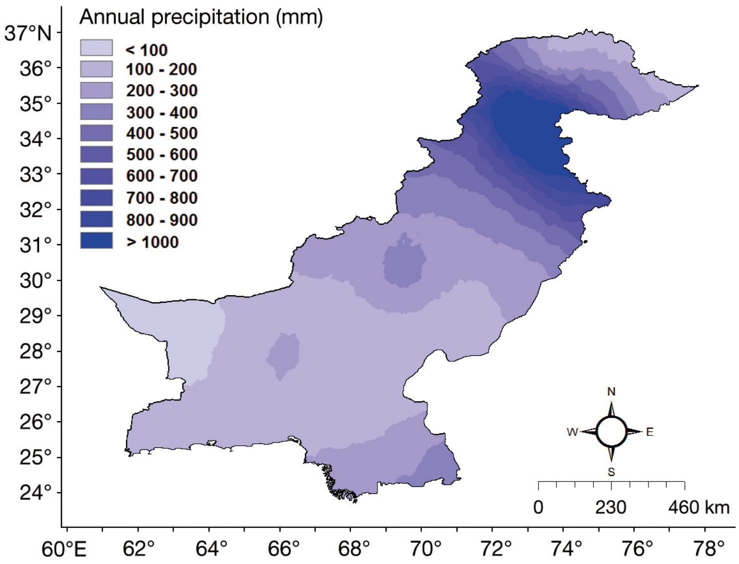

Fig. 2. Spatial patterns of mean annual precipitation (1961–2010) over Pakistan

variable and mostly unreliable (Jain et al. 2007, Naheed & Rasul 2011). The precipitation pattern of the pre-monsoon season is shown in Fig. 4a. The map shows that the major portion of the country receives precipitation of <40 mm while a very small area receives precipitation of >200 mm. The precipitation pattern of the post-monsoon season is shown in Fig. 4b. The lowest precipitation is recorded in this period. The majority of the area receives precipitation of <10 mm, while some northern parts receive >30 mm precipitation. Overall, the post-monsoon season can be considered as the driest season.

4.2. Trends in annual precipitation

The trend in annual precipitation was analyzed using the MK and MMK tests, while the rate of change in precipitation was estimated using Sen's slope method. Plus signs (+) in the figures indicate increasing trends at the 95% confidence level. The Sen's slope values obtained from 337 grid points were used to show the spatial pattern of annual precipitation changes (Fig. 5).

The significance of trends at the 95% confidence level obtained using the MK test is shown in Fig. 5a. Overall, there is non-significant increasing trend in annual precipitation in most parts of the country. Only a few areas show a significant increasing trend. The map also shows non-significant decreasing trends in some small areas in the north and western parts of the country.

The significance of trends at the 95% confidence level obtained using the MMK test is shown in Fig. 5b. The figure shows a reduction of significant change in annual precipitation from the MMK test compared to the MK test. The MMK test reveals a significant increase in precipitation only in the north in the sub-Himalayan Karakoram ranges (36–36.5° N, 73–74° E; 8126 m), at one grid located in Suleiman Ranges (29.5° N, 67.5° E; 3487 m) and 2 grids in the Punjab Plains (30.5° N–31° N, 72° E).

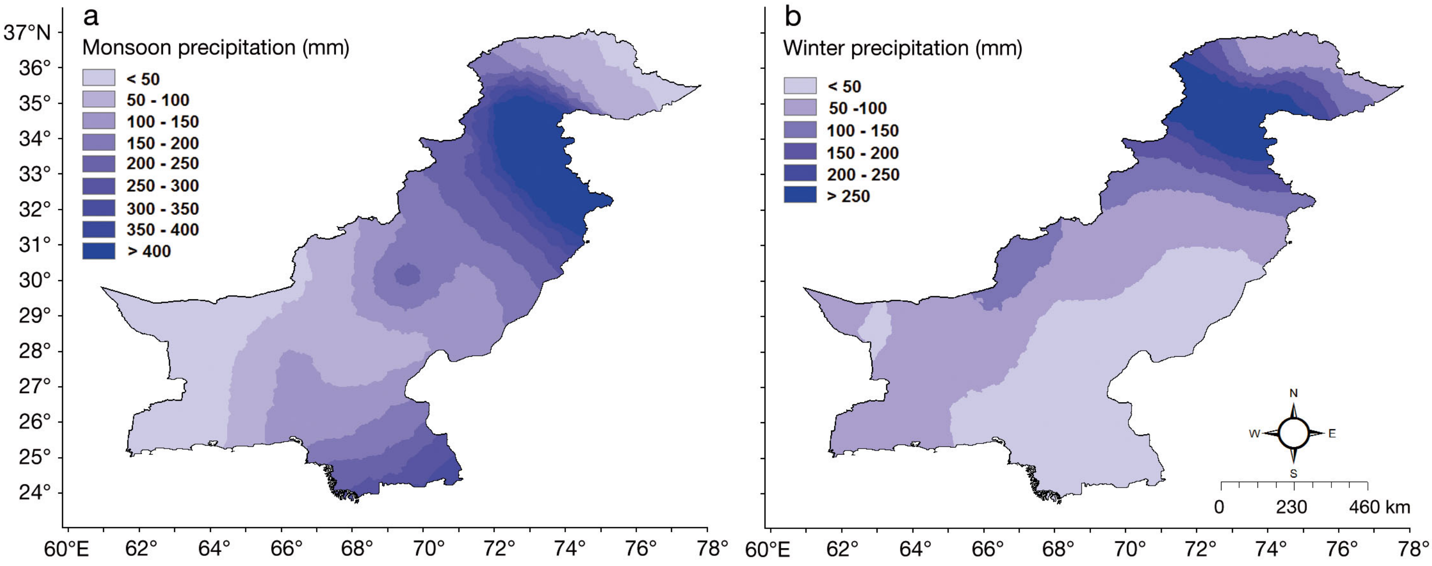

Fig. 3. Spatial patterns of (a) monsoon and (b) winter precipitation over Pakistan

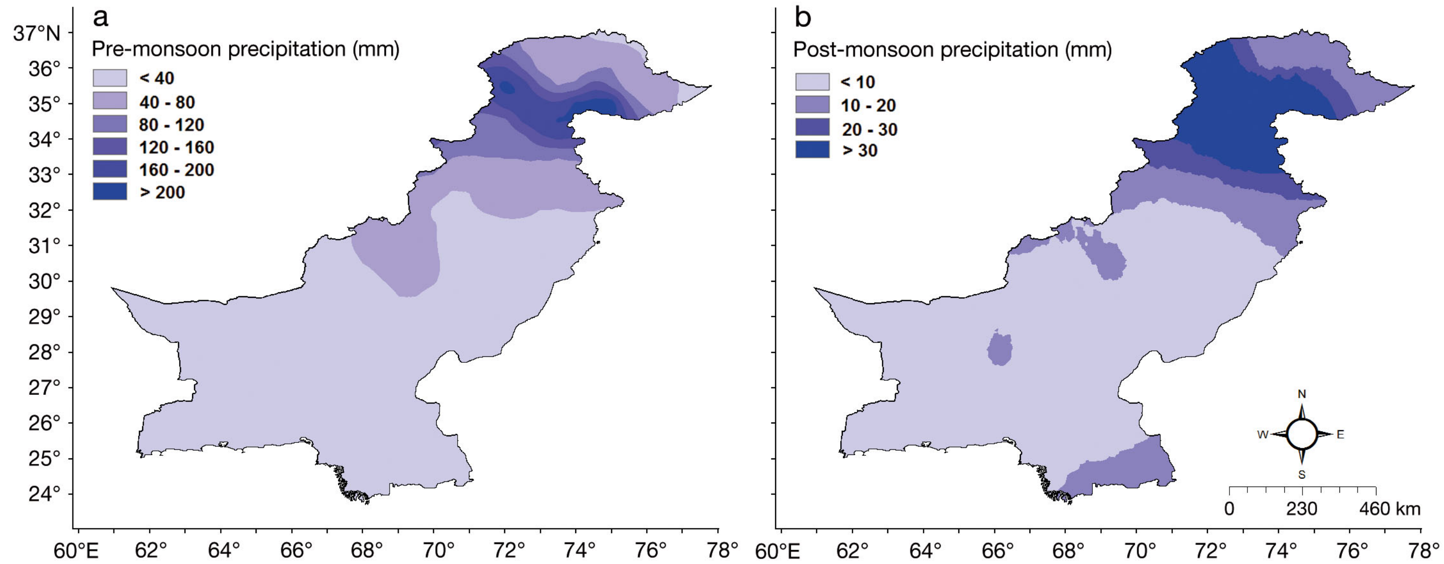

Fig. 4. Spatial patterns of (a) pre-monsoon and (b) post-monsoon precipitation over Pakistan

4.3. Trends in monsoon and winter precipitation

The trends in monsoon precipitation obtained using the MK and MMK tests are shown in Fig. 6a,b, respectively. The spatial distribution of the rate of change in monsoon precipitation obtained using Sen's slope method for the period 1961–2010 is shown in the figure. The values in the legend of the map represent the change in precipitation (mm yr^{-1}) during the monsoon. Since the monsoon contributes a major portion of the total annual precipitation, the magnitude of monsoon trends has a pattern similar to that of annual precipitation. The results showed increasing monsoon precipitation in most of Pakistan. A decrease in monsoon precipitation was also observed in some coastal areas in the southwest and southeast.

The MK test (Fig. 6a) shows increasing significant trends in some places in the north and northwest, where elevation is high. The MMK test (Fig. 6b) shows a reduction in significant trends in monsoon precipitation compared to that obtained using the MK test. Only a few grids mostly located in the north and northwest highlands showed a significant increasing trend. The decrease in monsoon precipita-

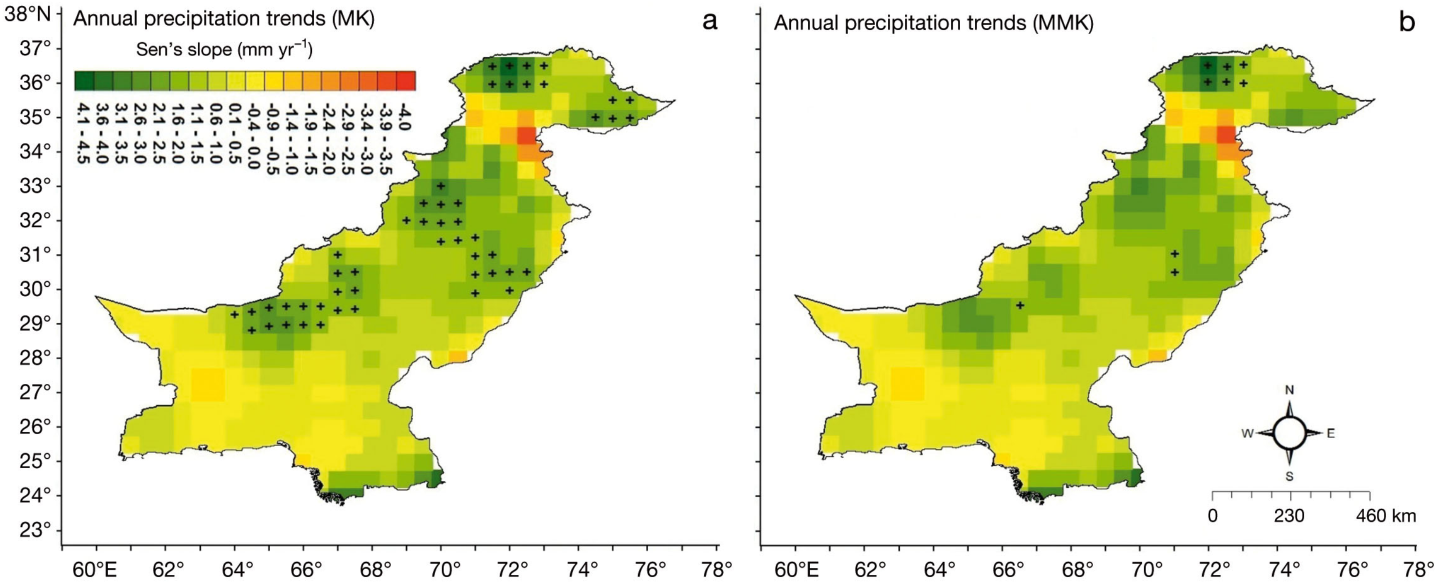

Fig. 5. Spatial patterns of trends in annual precipitation over Pakistan obtained using the (a) Mann-Kendall (MK) and (b) modified Mann-Kendall (MMK) tests. (+) Increasing trends at the 95 % confidence level

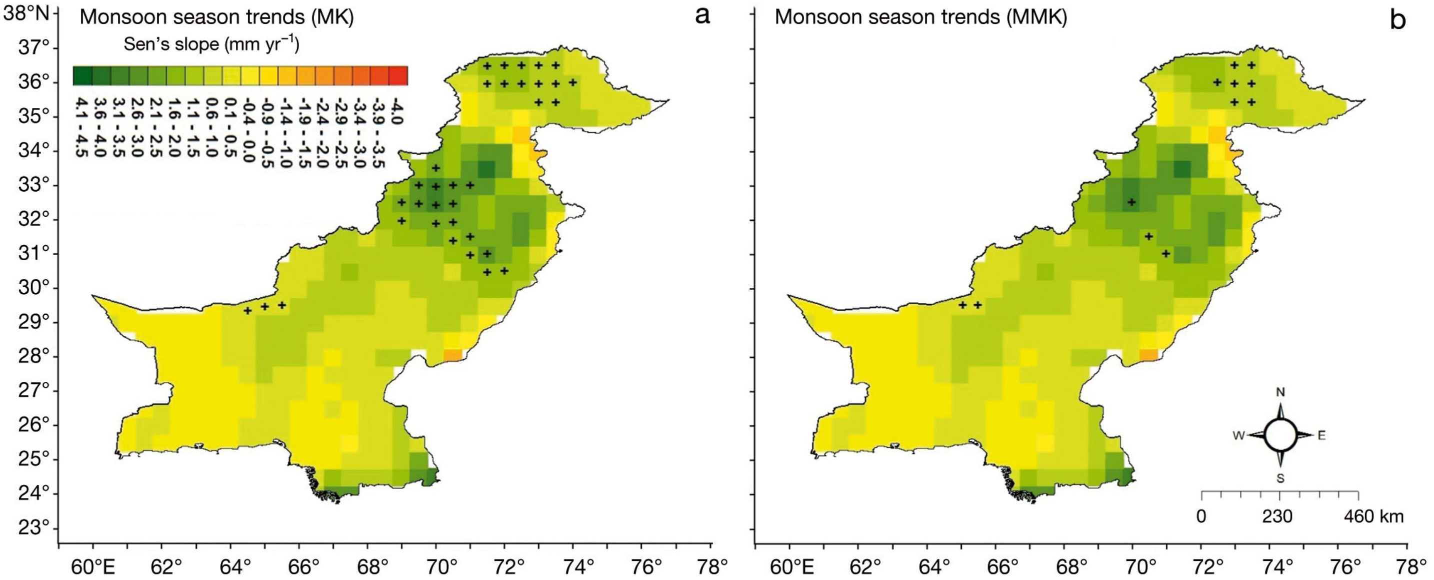

Fig. 6. Spatial patterns of trends in monsoon precipitation over Pakistan obtained using the (a) Mann-Kendall (MK) and (b) modified Mann-Kendall (MMK) tests. (+) Increasing trends at the 95% confidence level

tion was not significant at the 95% level of confidence by both the MK and MMK tests.

The rate of change in winter precipitation and the significance of change obtained using the MK and MMK tests are presented in Fig. 7a and 7b, respectively. The MK test showed a significant increase in winter precipitation over some parts of north and northwest Pakistan. These are mainly highlands where westerlies move across southwest Asia towards India. In contrast, the MKK test showed no significant change in winter precipitation at any grid point over Pakistan.

4.4. Trends in pre-monsoon and post-monsoon precipitation

Fig. 8a and 8b represent trends in pre-monsoon precipitation obtained using the MK and MMK tests, respectively. The spatial distribution of the rate of

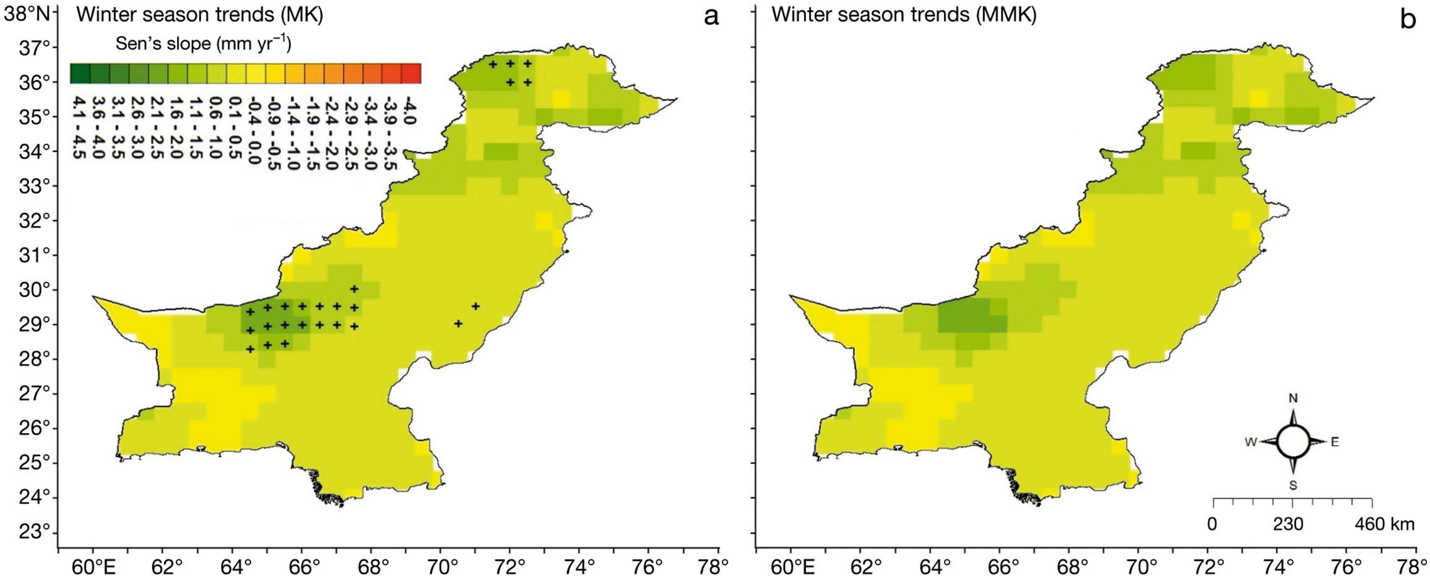

Fig. 7. Spatial patterns of trends in winter precipitation over Pakistan obtained using the (a) Mann-Kendall (MK) and (b) modified Mann-Kendall (MMK) tests. (+) Increasing trends at the 95% confidence level

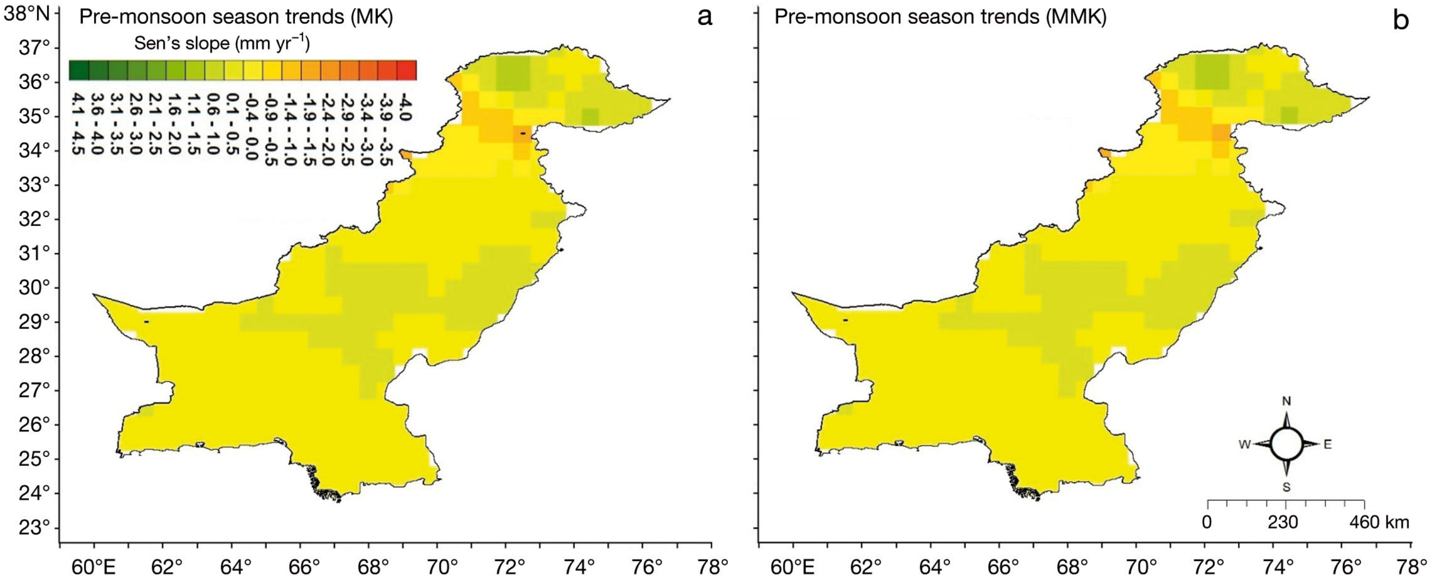

Fig. 8. Spatial patterns of trends in pre-monsoon precipitation over Pakistan obtained using the (a) Mann-Kendall (MK) and (b) modified Mann-Kendall (MMK) tests. (–): Increasing and decreasing trends at the 95% confidence level

change in pre-monsoon precipitation showed decreasing precipitation mostly over northwestern parts that generally receive higher precipitation during the winter season. However, both the MK and MMK tests found that the changes were not significant for most of Pakistan. The MK test detected a decreasing trend in pre-monsoon precipitation only at 2 grids, one located in the northeast sub-Himalayan range and the other located in the Siah Reg dunes in the northwest (29° N, 62.5° E) (Fig. 8a). The results of the MMK test (Fig. 8b) indicate that precipitation significantly decreased only at one grid located in the northwest (29° N, 62.5° E).

The trends of post-monsoon precipitation obtained using the MK and MMK tests are depicted in Fig. 9a and 9b, respectively. It is clear from the figure that post-monsoon precipitation has decreased in most of the country, except in the north, center and southeast parts. The MK test indicates significant decreasing trends at the 95% confidence level in the southern

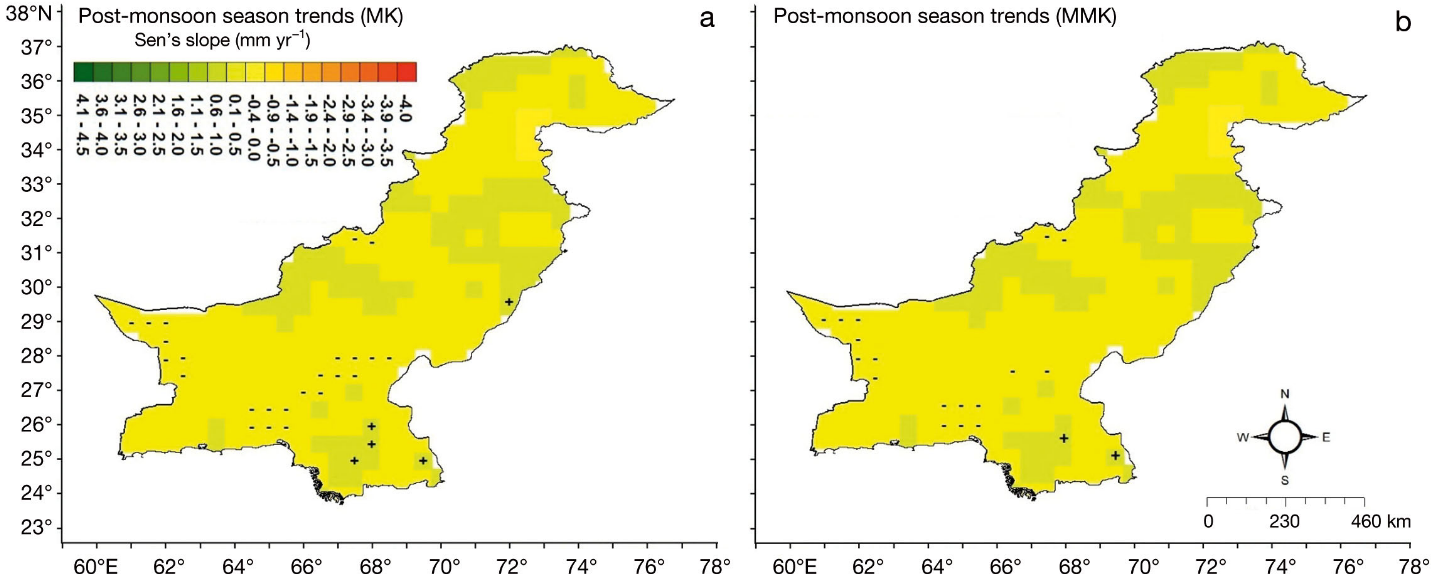

Fig. 9. Spatial patterns of trends in post-monsoon precipitation over Pakistan obtained using the (a) Mann-Kendall (MK) and (b) modified Mann-Kendall (MMK) tests. (+,–) Increasing and decreasing trends at the 95% confidence level, respectively

plains and in the hyper-arid Kharan desert in the northwest (28° N, 68° E) of the country. A significant increase is also observed in the Sindh plains (25° N, 69° E) located in the southeast. The results of the MMK test show a reduction in significant trend as compared with MK tests. However, the MKK test also detected some significant decreasing trends in the Kharan desert located in the northwest and central part of Makran coast in the south.

5. DISCUSSION

The annual and seasonal precipitation trends obtained using the MK test correspond to the findings of previous studies. A number of recent studies have reported trends of increasing monsoon precipitation across Pakistan (Hanif et al. 2013, Ahmad et al. 2015, Shaw 2015). In the present study, the MK test also showed a significant increase in monsoon precipitation in the north and the northwest. Increasing winter precipitation as obtained in the present study using the MK test has also been reported by Farooqi et al. (2005), Mitra & Sharma (2010) and Ringler & Anwar (2013). However, the number of grids showing a significant trend in annual and seasonal precipitation using the MK test was reduced significantly when the MMK test was used. The MMK test also revealed no significant change in winter precipitation at any grid point over Pakistan.

A number of studies conducted in recent years have revealed a reduction of significance in trends in hydro-climatic data when MMK tests are used (Khaliq et al. 2009, Kumar et al. 2009, Hodgkins & Dudley 2011, Lacombe & McCartney 2014, Shahid et al. 2014, Dudley et al. 2017). These studies suggested that the significant trends using the MK test in different regions resulted from ignoring the natural variability of the climate. The present study also suggests that many of the significant precipitation trends obtained using the MK test resulted from ignoring the effect of LTP.

The significance of the hydro−climatic trends over time is very sensitive to the assumptions of whether the underlying data have short- or long-term persistence. The recent IPCC report (IPCC 2013) suggested that the significance of trends estimated by first-order autoregressive models may not be valid when tested against a process that supports the existence of 'long-range dependence'. Therefore, a number of recent studies cast doubt on the results that were previously obtained without considering multi-decadal variability in time series (Kumar et al. 2009, Ehsanzadeh & Adamowski 2010, Lacombe et al. 2012, Shahid et al. 2014, Fathian et al. 2015). The results of the present study also suggest that many of the trends in annual and seasonal precipitation obtained using the MK test may be affected by the scaling effect, which means that the climatic trends in Pakistan should be evaluated using the MMK test.

The results using the MMK test suggest that annual and monsoon precipitation have increased only in the sub-Himalayan Karakoram Range in northwest Pakistan and at a few GPCC points located in the regions of the Suleiman Ranges and the Punjab Plains. Winter precipitation has not changed at any location in Pakistan, while pre-monsoon precipitation has decreased only at a single grid point located in the Siah Reg dune in the northwest Kharan desert. The post-monsoon precipitation has decreased in the northwest Kharan desert and the central part of the Makran coast located in the south, and increased in the Sindh plains located in southwest Pakistan. Overall, the results revealed that annual and seasonal precipitation in Pakistan has increased at grid points that are mostly located at higher altitudes and decreased at the points located in the plains.

Kripalani et al. (2007) reported that an increase in south Asian precipitation is due to an increase in water vapor transport from the Bay of Bengal and the Arabian Sea. Preethi et al. (2017) recently found a westward shift of the monsoon that may transport more moisture and results in more rain over Pakistan. Recent studies have also reported intensification of monsoon precipitation in the region (e.g. Wang et al. 2011). The intensified monsoon results mainly from an enhanced land−sea contrast and a northward shift in the convergence zone. The monsoon is also found to be sensitive to the increase in atmospheric concentrations of greenhouse gases and aerosols, and the associated changes in radiative forcing (Sajani et al. 2012). Several general circulation models predicted strong Asian monsoons due to doubling of CO_2 in the atmosphere (Tyson et al. 2002). Menon et al. (2013) also reported that there will be consistent increases in monsoon precipitation in the future. The strengthening of northward moisture transport over the Arabian Sea is also reported as a likely reason for the significant positive trend of monsoon precipitation in Pakistan. In addition, extra-tropical phenomena are influencing the mean monsoon precipitation trends by enhancing the cross-equatorial flow of moisture into the Arabian Sea (Latif et al. 2017). Therefore, it can be remarked that changing atmospheric phenomena due to global warming may bring more monsoon precipitation in the future.

Afzal et al. (2013) also showed that the negative phase of the Southern Oscillation is directly responsible for above-normal precipitation over the northern highlands, whereas the cooling ocean surface over the central Pacific causes suppressed winter precipitation. This indicates decadal variability in winter precipitation influenced by the Southern Oscillation (Adnan et al. 2016). The MK test does not consider the long-term variability in time series. Therefore, it detected a significant increase in winter precipitation in the northern part and northwestern highlands of Pakistan. The present study reveals that the changes in winter precipitation detected in previous studies are due to decadal variability.

The present study showed that pre-monsoon precipitation has decreased only at a single grid point. The decrease in pre-monsoon precipitation may be due to the reduction in convective activities which has been observed over India in recent years (Guhathakurta & Rajeevan 2008, Krishnakumar et al. 2009).

6. CONCLUSIONS

The trends in seasonal and annual precipitation of Pakistan are analyzed in this study using 2 versions of the MK trend test to assess the effects of LTP on detection of the trends. The results show that LTP has a significant effect on the precipitation trends of Pakistan. The trends in annual, monsoon and winter precipitation are significantly affected by LTP. The trends in post-monsoon precipitation are less affected by LTP. The extent of the effect of LTP is consistent across the entire country.

The present study reveals that the annual precipitation in Pakistan is increasing only in the north and in a few northeastern locations. The significant increase of annual precipitation in those regions mainly results from a significant increase in monsoon precipitation. There is no significant change in winter precipitation. The MK test detected a significant increase in winter precipitation at some points mostly located in the zones influenced by the Mediterranean climate. However, the MMK test revealed that all of those trends result from the scaling effect. Post-monsoon precipitation is found to decrease significantly at many points located in southwestern low precipitation zones.

This study provides an elaborate view of recent trends in the precipitation of Pakistan. The incorporation of LTP has provided better information regarding the regions with significant precipitation trends. In addition, the maps of the spatial patterns of seasonal precipitation and their trends can provide improved information on seasonal precipitation. It is expected that the findings of the present study will help in planning and management of agriculture and water resources of Pakistan.

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