Asia-Pacific J. Atmos. Sci., 49(4), 421-441, 2013
DOI:10.1007/s13143-013-0039-5

The Regional and the Seasonal Variability of Extreme Precipitation Trends in Pakistan

Mian Sabir Hussain and Seungho Lee

Department of Geography, Konkuk University, Seoul, Korea

(Manuscript received 26 July 2012; revised 11 December 2012; accepted 15 December 2012)

Abstract: The variability of spatial and temporal trends in extreme precipitation indices and the trend directions were studied for the meteorological seasons of 1950 to 2010. A daily precipitation dataset from 15 weather stations in Pakistan was used. Seven indices were chosen: total precipitation from events ≥ 90th, 95th, and 99th percentiles, the number of days with precipitation ≥ 90th, 95th, and 99th percentiles of daily precipitation amounts, and annual dry days. A study investigating temporal changes in the spatial extent of statistically significant extreme precipitation events was performed. Trends were calculated for each of the 30-year moving periods within the 1950-2010 time period using a simple linear regression technique and Kendall's tau-based slope estimator. A distinct spatial differentiation appeared in the prevailing directional trends between the northern and southwestern parts of the study area. In all seasons, increasing trends in extreme precipitation dominated in northeastern Pakistan, whereas a reducing tendency towards extreme precipitation prevails in the southwestern part of the country.

Key words: Extreme precipitation, trend direction, trend stability, seasonal change, Pakistan

1. Introduction

Extreme precipitation is one of the most challenging and popular topics in the climate sciences. Variation in the occurrence and intensity of extreme precipitation is considered to be evidence of climate change. Numerous studies have shown that extreme climate conditions vary significantly with location and time. Accordingly, such changes impact human lives, communities, health, welfare, agriculture, and economies (Smadi and Zghoul, 2006; Raj and Azeez, 2010; Toros, 2011).

Understanding the variability of extreme precipitation, on both short- and long-term time scales, is becoming a priority for researchers. Several researchers have analyzed the variability of extreme precipitation in various regions of the world (Brunetti *et al.,* 2001; Harju *et al.,* 2010; Iwasaki, 2010; Lupikasza *et al.,* 2010; Park *et al.,* 2010; Gillies *et al.,* 2011; Li *et al.,* 2011), and numerous studies have reported trends of increasingly heavy precipitation (Mason and Joubert, 1997; Frei and Schar, 2000; Roy and Balling Jr., 2004; Schmidli and Frei, 2005; Nastos and Zerefos, 2007, 2008; Burt and Ferranti, 2010; Iwasaki, 2010; Ravadekar and Preethi, 2010; Deshpande *et al.,* 2011). Regional studies indicate complex and non-uniform spatial patterns of extreme precipitation (Hassan *et al.,* 2011; Raziei *et al.,* 2011). Significant positive trends in annual extreme precipitation were detected by several climatologists in various parts of the world (Mason *et al.,* 1999; Haylock and Nicholls, 2000; Kunkel, 2003; Dravitzki and McGegor, 2010; Naumann *et al.,* 2010). In contrast, a number of studies of seasonal changes of precipitation extremes were carried out, and noticeably decreasing trends were confirmed (Schmidli and Frei, 2005; Zolina *et al.,* 2008; Lupikasza 2010). Hence, extreme precipitation and its consequences have generated great interest from a broad spectrum of the scientific community. Many researchers have concluded that extreme precipitation events are the major cause of severe floods worldwide (Frei and Schar, 2000; Svensson and Jakob, 2002; Kunkel 2003; Park *et al.,* 2010), and this is certainly true of Pakistan (Afzal and Zaman, 2010; Aziz and Tanaka, 2011; Hassan *et al.,* 2011), where floods of the last years have done damage.

In recent times, with increasing concerns about the impacts of climate change, scientists have employed different statistical techniques to identify trends in the spatiotemporal variability of precipitation and extreme precipitation events. Non-parametric statistical procedures have often been applied to confirm the results of more conventional techniques, such as moving averages and regression analysis. Within this context, many studies of variations in precipitation have been carried out in recent years, and these studies have provided a great deal of insight into the direction and the significance of precipitation trends within their specific regions of interest (Turkes, 1996; Schmildi and Fres, 2005; Samadi and Zaghoul, 2006; Cloiero *et al.,* 2011; Samba and Nganga, 2011; Toros, 2011). The changing patterns of extreme precipitation and their impacts on surface water resources are important climatic problems today. The implications of these changes are particularly significant for areas which are already under stress, such as regions which experience water shortages through the combination of a dry climate and a highly seasonal precipitation regime.

Trends of extreme precipitation depend strongly on the study period and on the season, and hence, an approach that aids the evaluation of highly variable precipitation over time and space is needed. The results of trend analysis depend strongly on

Corresponding Author: Seungho Lee, Department of Geography, College of Science, Konkuk University, 120 Neungdong-ro, Gwangjin-gu, Seoul 143-701, Korea.
E-mail: leesh@konkuk.ac.kr

values at the beginning and end of the time series (Lupikasza, 2010). For an overview of the trends in extreme precipitation indices, a moving 30-year trend analysis is used to analyze changes in significant extreme precipitation trends. A seasonal approach to examining the trends in extreme precipitation has been adopted at the scale of Pakistan. The main objective of this study is to examine changes in extreme precipitation over Pakistan during the period of 1950 to 2010. In particular, total annual extreme events, seasonal extreme precipitation, and the number of rainy days will be discussed in detail.

2. Precipitation climatology in Pakistan

The arid climate of Pakistan, characterized by hot summers and cold winters, occurs over the whole of the Sindh Province, the southern part of the Punjab, central parts of the northern areas, and the southern part of Baluchistan (Hussain and Lee, 2009). The dry conditions that prevail over most of the country do not occur on the southern slopes of the Himalayas and in the sub-Himalayas (Shirazi, 2006). The amount and timing of precipitation and its distribution across Pakistan are controlled predominantly by the annual monsoon system and western disturbances. In Pakistan, 50% to 75% of the precipitation is associated with the summer monsoon; western disturbances are the major cause of winter precipitation (Kazi, 1951; Khan, 1993; Hussain and Lee, 2009). One of the main characteristics of the climate in Pakistan is the irregular distribution of precipitation and its high variability in terms of time, space, amount, and duration, however few studies have addressed this important topic within Pakistan.

In regard to monthly precipitation climatology, about 56% of annual precipitation occurs from June to September in Pakistan, but maximum precipitation occurs in July-August (41.3%) and March (9.5%), lower values are recorded in November-December, and generally uniform monthly amounts of precipitation occur from January to April. All precipitation regions (Hussain and Lee, 2009) of the study area are subject to a considerable degree of precipitation seasonality. This division

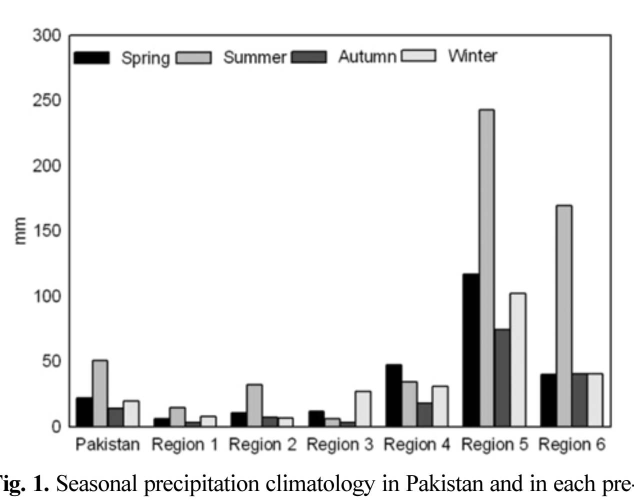


Fig. 1. Seasonal precipitation climatology in Pakistan and in each precipitation region studied (1950-2010).

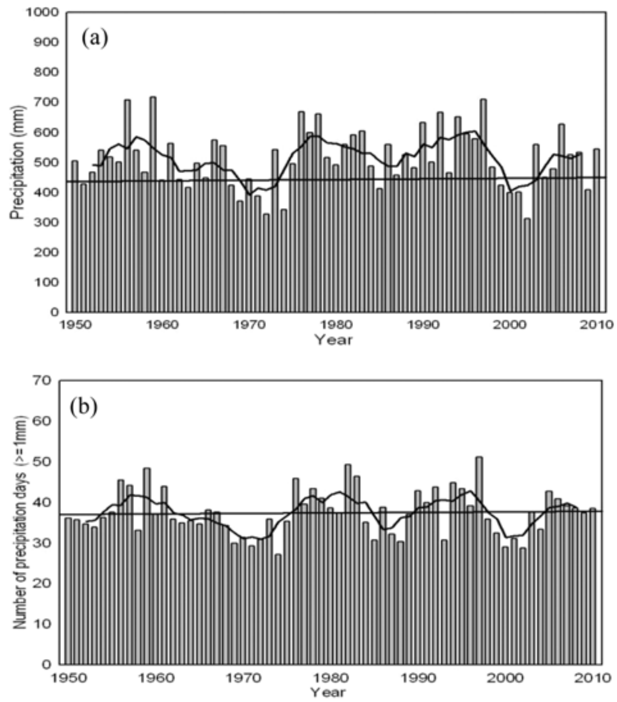


Fig. 2. Time series of annual precipitation (a) and number of precipitation days (b). Bars represent annual values, solid line is linear trend and solid curves are moving averages of 5-years.

of the study area into six areas made geographical sense, as they are each characterized by a particular precipitation regime. Note that the regional means of seasonal precipitation shown in Fig. 1 are weighted according to the number of weather stations in each region. Region 1 is mainly characterized as the region by having the lowest amount of precipitation. In this region, 45.6% of total precipitation occurs during the summer season, while autumn can be referred to as a dry season. Region 2 differs from region 1 because of the large amount of precipitation which occurs during the spring season. Region 3 is the next neighboring region of region 1, but differs from region 1 because of the greater importance of winter precipitation. This region can be distinguished by having the lowest amount of summer precipitation. The reason for the occurrence of more winter precipitation is the influence of western disturbances. Region 4 is characterized by receiving high amounts of spring and winter precipitation. Region 5 is the wettest part of the country, and can be characterized by having the highest amount of precipitation in the summer season. This region also receives a large amount of precipitation during spring, autumn, and winter seasons. In contrast, summer precipitation is greater in region 6 than in region 5. Figure 2 depicts the course of the annual precipitation time-series and the number of precipitation days.

3. Data and methodology

Daily precipitation data from 15 weather stations in Pakistan during the period of 1950 to 2010 were obtained from the

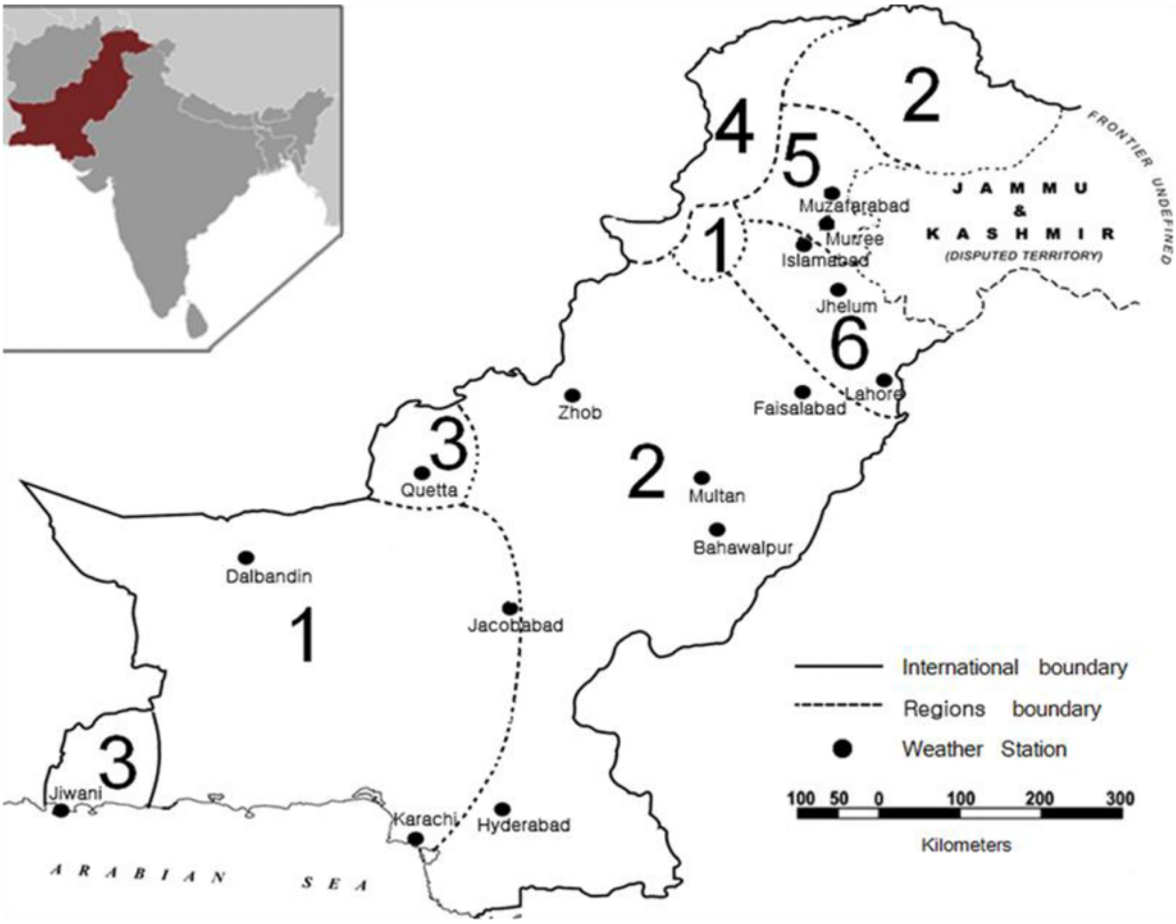


Fig. 3. The location of the 15 weather stations and limits of 6 precipitation regions used in this study for the period 1950-2010.

Table 1. Acronyms and definitions of the extreme precipitation indices used in this study.

Acronym	Description/explanation	Unit
90pT	Precipitation total from events ≥ 90th percentile of daily precipitation amount at wet days ≥ 1 mm in the period 1971-2000	mm
95pT	Precipitation total from events ≥ 95th percentile of daily precipitation amount at wet days ≥ 1 mm in the period 1971-2000	mm
99pT	Precipitation total from events ≥ 99th percentile of daily precipitation amount at wet days ≥ 1 mm in the period 1971-2000	mm
90pNoD	Number of days with precipitation ≥ 90th percentile of daily precipitation amount at wet days ≥ 1 mm in the period 1971-2000	days
95pNoD	Number of days with precipitation ≥ 95th percentile of daily precipitation amount at wet days ≥ 1 mm in the period 1971-2000	days
99pNoD	Number of days with precipitation ≥ 99th percentile of daily precipitation amount at wet days ≥ 1 mm in the period 1971-2000	days
TNoDD	Total annual number of dry days	days

Pakistan Meteorological Department (PMD) and were used in the present study. The stations are fairly evenly distributed throughout Pakistan and well represent the precipitation of the study area (Fig. 3). One of the most significant characteristics of this dataset is that it is the longest available time series of daily precipitation records of Pakistan.

Extreme precipitation can be defined in several ways, depending on the objectives of the study, the region, and the type of data used in the study. To cover long-term trends of a range of characteristics in precipitation extremes, a number of diagnostics can be considered. Generally, there are two basic groups of extreme precipitation indices. Thresholds for defining days with extreme precipitation may be based on arbitrary values such as 10 mm, 50 mm, or 80 mm or on statistical quantiles such as the 90^{th} percentile, 95^{th} percentile or 99^{th} percentile. Various diagnostics or indices of extreme precipitation thresholds have been suggested by numerous scientists (e.g., Zolima *et al.,* 2002; Harju *et al.,* 2010; Lupikasza, 2010). These indices provide the best information about extreme precipitation occurrence and precipitation totals from extreme events. In this study, seven indices of extreme precipitation were used to describe the frequency and magnitude of heavy precipitation events (Table 1).

The 90th, 95th, and 99th percentile values for wet days with precipitation ≥ 1 mm were calculated individually for each season in the reference period of 1971-2000. The following seasons were adopted: spring (MAM), summer (JJA), autumn (SON), and winter (DJF). Hussain and Lee (2009) classified precipitation regions in Pakistan (Fig. 3). The identified precipitation regions successfully follow the rainfall division of Pakistan according to physical features. The present research addresses changes in extreme precipitation for which the trend is generally increasing or decreasing.

Long-term trends of climate variables are usually detected by linear regression. In the present study, trend direction was determined using the least squares linear regression method. Moreover, Kendall's tau-based slope estimator is applied on the dataset to compare the results of the two methods. The main advantage of the Kendall's tau-based test is that it is nonparametric and does not assume the distributional form of the investigated data (Zhai *et al.,* 2004; Field, 2005). Owing to its large spatial and temporal variability, precipitation trends have a lower statistical significance than other climate elements. Therefore, trends are identified as being statistically significant when $p \leq 0.1$ (Lupikasza, 2010). The directions of long-term trends of both information variability and spatial stability are needed, and hence, a moving 30-year period is used in trend analysis.

Evaluating the persistence of trend directions over all the 30-year periods provides a clear indication of trend stability within the entire study period. The derived trend information does not depend on extreme high or low values at the beginning and end of the entire time period. Linear trends and Kendall's tau-based slope of extreme precipitation indices were determined separately for each station and each of the moving 30-year periods within the period of investigation, 1950-2010. According to the length of the observation period, 32 linear trends were calculated for each weather station. The stability of trends of extreme precipitation was determined using statistical significance and the direction of trends for all moving 30-year periods. This was expressed as the percentage of the 30-year periods (T) during which these trends were statistically significant. Lee *et al.* (2011) applied this technique successfully to determine the trend stability of extreme precipitation in South Korea. In addition, stations with predominantly significant positive trends were differentiated from those having a majority of significant negative trends. All of the calculations were performed for all of the standard weather stations.

4. Results

a. Annual variability in trends of extreme precipitation indices

Long-term annual trends of the indices of extreme precipitation dominated over large areas of Pakistan during the period of 1950-2010. In the spatial perspective, positive trends are prominent in the studied areas. The values vary with the index used, with 68% (90pNoD) to 48% (95pNoD) to 40% (99pNoD) and 48% (90pT) to 33% (99pT) of stations having statistically significant increases of days with extreme precipitation and in precipitation totals from extreme events, respectively. At the beginning of the data series, most of the trends for the initial 30-year periods (1950-1979) were significantly increasing, except for 95pT and 99pNoD, which showed decreasing trends. Over the long-term, the 30-year periods (1950-1979 to 1970-1999) showed increasing trends for 90pNoD, 90pT, 95pNoD, and 99pNoD.

The 30-year periods (1971-2000 to 1981-2010) showed significant downward trends for 90pNoD, 90pT, 95pNoD, and 99pNoD. Statistically significant decreasing trends of extreme precipitation days and totals were present from the 30-year periods starting in the early 1950s (1951-1980) and continued to the beginning of the 1960s (1961-1990) for 90pNoD, 90pT, and 95pNoD. Decreasing trends covered the largest number of stations during 1975-2004, when 40% of the stations recorded such trends for 90pNoD, and during 1968-1997, when 33% of stations recorded such trends for 99pT. After 1971-2000, the 30-year periods indicate no statistically significant upward trends for any indices, except for 95pT and 99pT. Positive trends in this time period covered the largest number of stations during the 30-year periods of 1979-2008 and 1981-2010, when 13% and 6% of the stations recorded such trends for 95pT and 99pT, respectively. Overall, the territorial extent of both positive and negative trends varied, and trends of 30-year periods moved in both directions (Fig. 4).

To the results of the Kendall tau-based test varied according to the index used, with 80% (90pNoD) to 48% (95pNoD) to 40% (99pNoD) and 54% (90pT) to 54% (95pT) of stations having statistically significant increases of days with extreme precipitation and in precipitation totals from extreme events. The result pattern of Kendall's tau-based slope is similar to the results of the linear trend. However, the results showed significant increasing trends for 95pT (Fig. 5).

b. Long-term seasonal variability

In the spring season, the highest percentage of stations with significant trends, independent of their direction, was observed for 90pT, 90pNoD, 95pT, and 95pNoD. The maximum percentage of positive trends within a single 30-year period reached 28% for 90pT and 54% for 90pNoD and 28% for 95pT and 40% for 95pNoD. The values of 90pT and 90pNoD and 95pT and 95pNoD were recorded for 1954-1983 and 1968-1997, respectively. The frequency of significant positive and negative trends was almost equal, if averaged over all 30-year periods. The maximum percentage of negative trends within a single 30-year period reached 54% for 90pT and 68% for 90pNoD and 48% for 95pT and 68% for 95pNoD. The values of 90pT, 90pNoD, 95pT, and 95pNoD were recorded for 1981-2010.

The general characteristics of spring trends showed that these trends clearly varied and were linked to similar changes

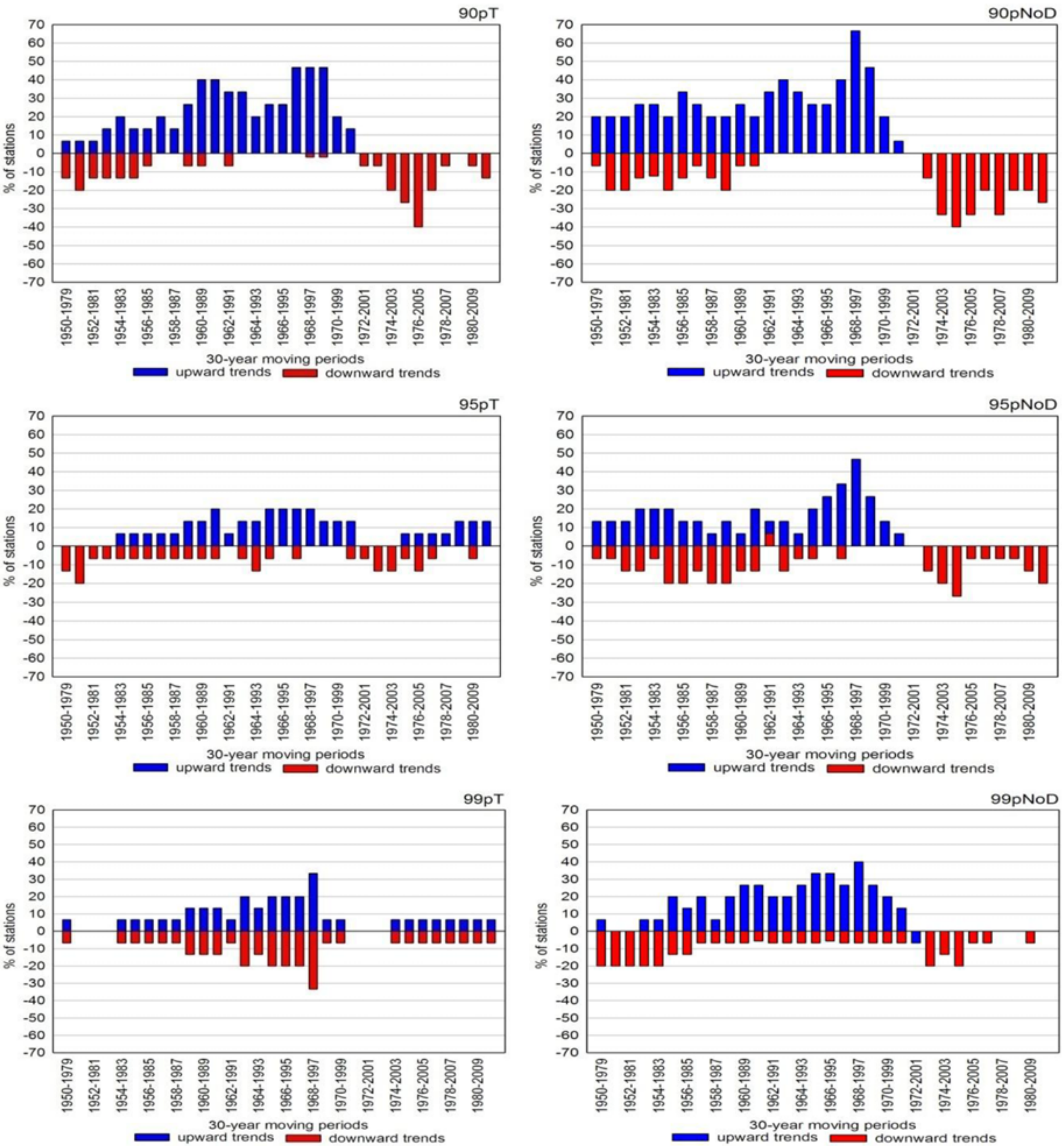


Fig. 4. Percentage of stations (increasing/decreasing) with statistically significant trends in annual extreme precipitation indices in Pakistan in moving 30-year periods. The trend is significant at $p \leq 0.1$.

in the characteristics of the annual trends. During the 30-year periods following the early 1970s, the percentages of stations with significant positive trends were considerably smaller for 95pNoD, 95pT, 90pNoD, and 90pT. The spatial extent of significant decreasing trends averaged over all 30-year periods varied between 6% and 68% (90pNoD, 90pT, 95pNoD, 95pT) and 6% and 20% for 99pT and 99pNoD. The most distinctive feature of temporal variability in extreme precipitation trends during the spring season is their considerable decline since 1972 for all of the investigated indices.

The regional extent of significant trends was largest in the summer. The summer season showed the most pronounced temporal changes in the percentage of significant trends, positive in the 1950s and 1960s and negative in the remaining period. The percentage of stations with statistically significant trends, independent of their direction and averaged over all 30-year periods, varied from 28% (90pT) to 33% (90pNoD). For positive trends, the percentages for individual 30-year periods were higher, such as that of 33% (90pNoD) in 1951-1980, 33% (90pT) in 1960-1989, 33% (95pNoD) in 1954-1983, 28% (95pT) in 1960-1989, 28% (99pNoD) in 1960-1989, and 28% (99pT) in 1960-1989. For negative trends, the percentages for individual 30-year periods were also higher, such as 12% (90pNoD) in 1956-1985, 28% (90pT) in 1978-2005, 12%

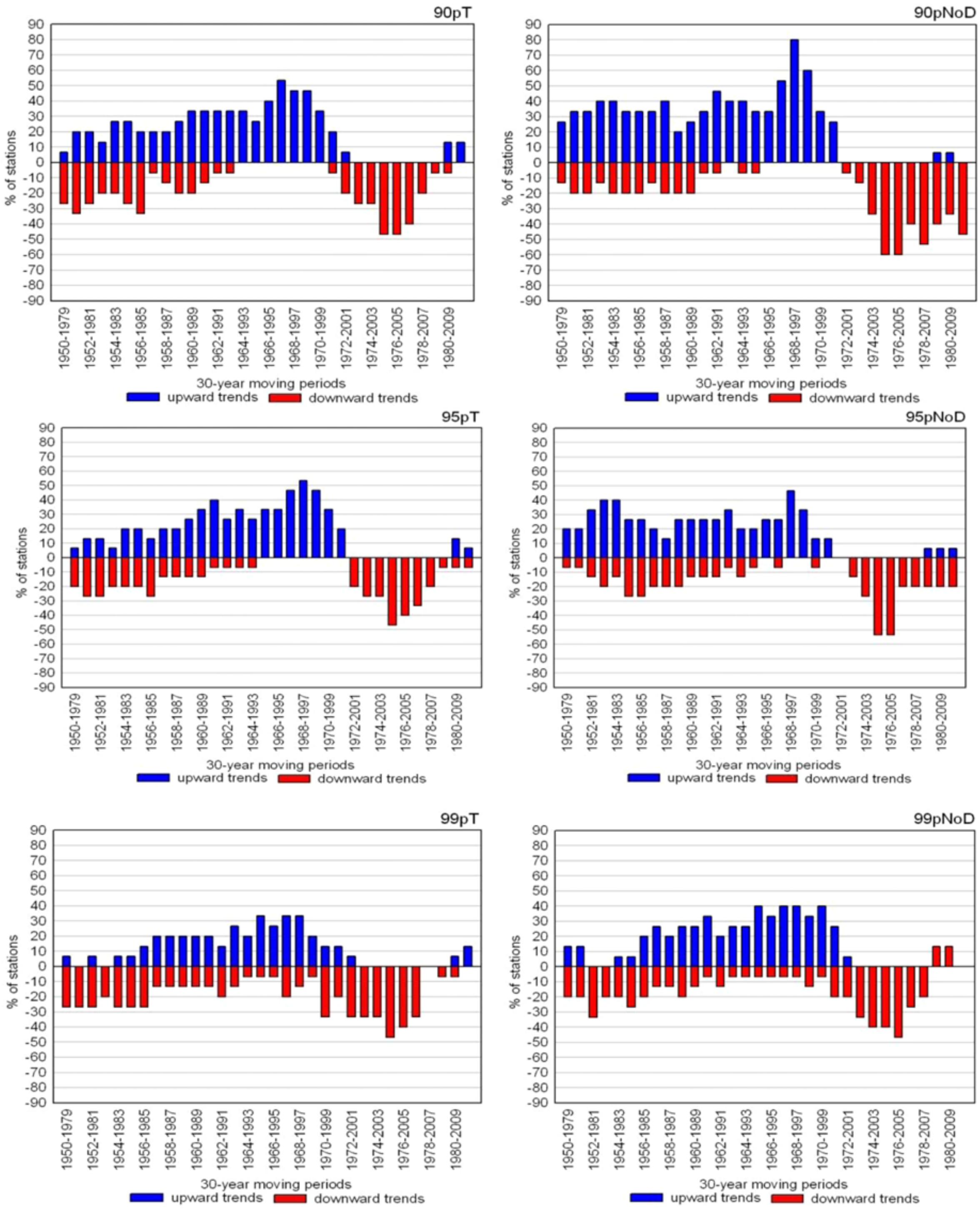


Fig. 5. Same as Fig. 4, but using Kendall's tau-based slope estimator.

(95pNoD) in 1972-2001, 20% (95pT) in 1976-2005, 12% (99pNoD) in 1981-2010, and 12% (99pT) in 1975-2005. The regional extent of decreasing trends averaged over all indices (16%) was smaller than that for increasing trends (30.5%).

In the summer season, the percentage of significant negative 30-year trends gradually increased from 1972. Positive trends were particularly pronounced for all of the indices until 1972. After 1972-2001, the percentage of stations with negative trends increased rapidly until 1978-2007. These temporal changes are the most prominent feature of summer extreme precipitation trends. In subsequent 30-year periods, the percentage of positive trends increased slightly in a second phase from 1978-2007 to 1981-2010 (90pT, 95pT, 99pT, and 99pNoD), with a highest value of 6% (Fig. 6).

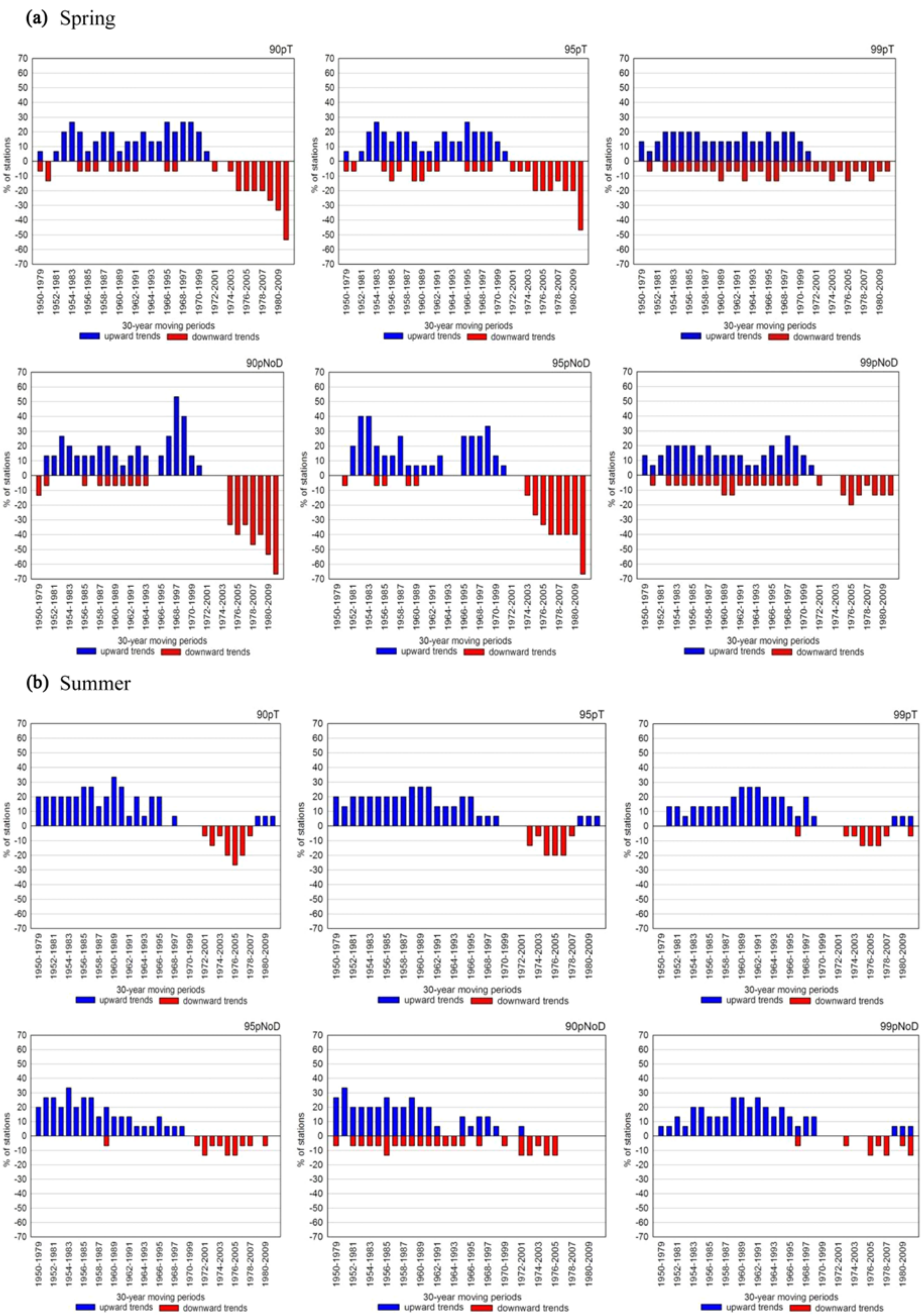
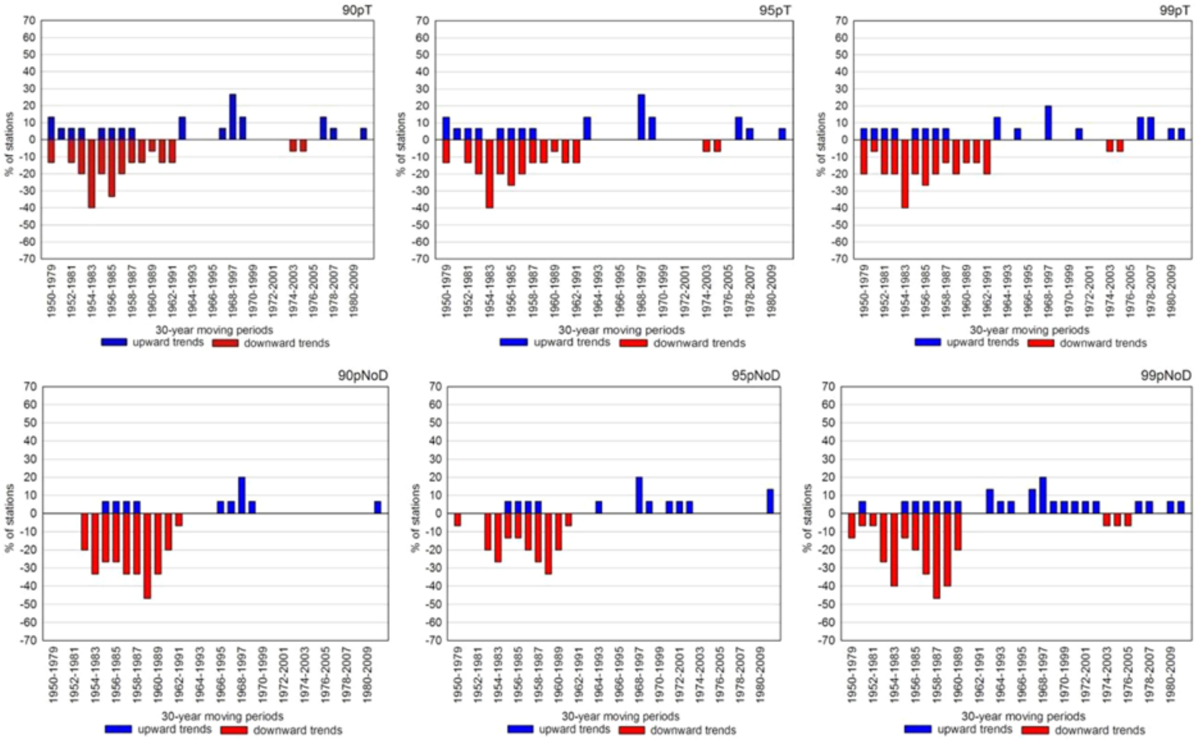


Fig. 6. Percentage of stations (increasing/decreasing) with statistically significant trends in annual extreme precipitation indices in Pakistan in moving 30-year periods: (a) Spring, (b) Summer. The trend is significant at $p \leq 0.1$.

(a) Autumn



(b) Winter

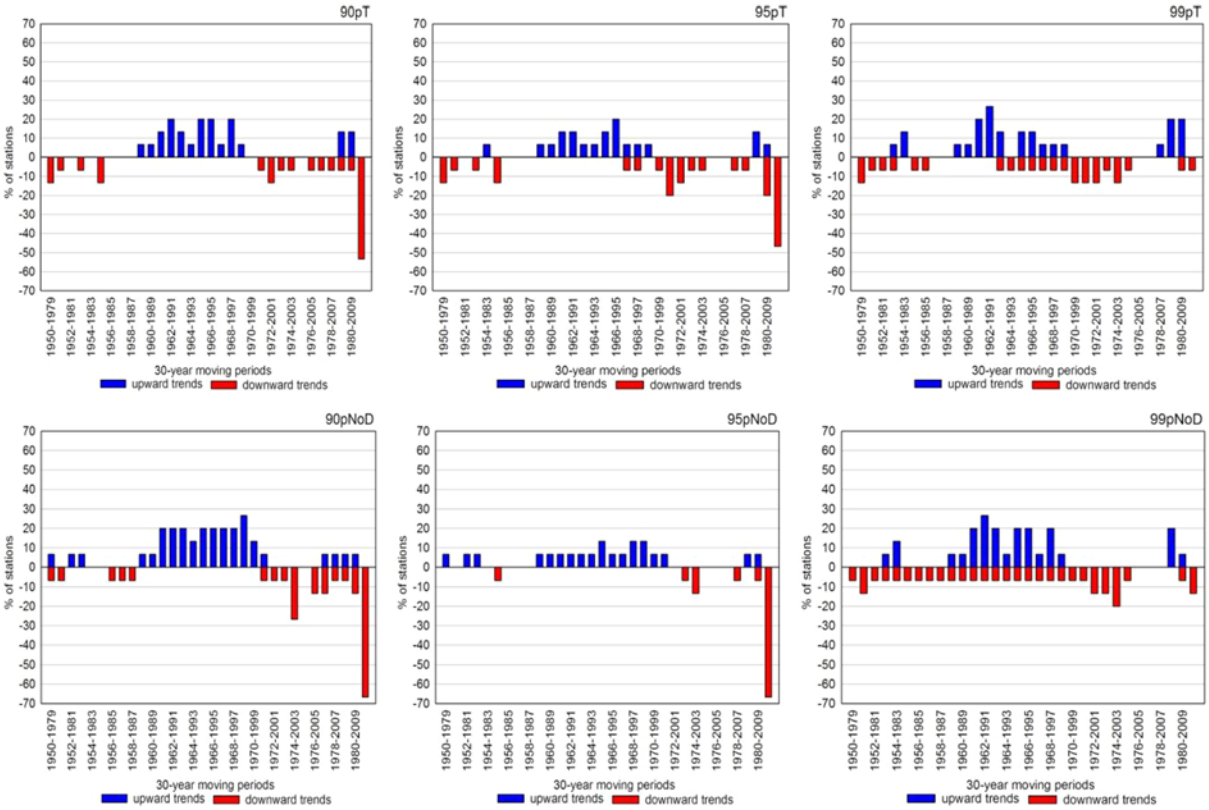


Fig. 7. Percentage of stations (increasing/decreasing) with statistically significant trends in annual extreme precipitation indices in Pakistan in moving 30-year periods: (a) Autumn, (b) Winter. The trend is significant at $p \leq 0.1$.

On average (over all sub-periods and indices), results showed a low frequency of increasing and high frequency of decreasing trends of significant extreme precipitation in autumn. Despite this spatial difference of significant trends, a pattern of temporal changes emerges. The temporal changes for the autumn season are very different than those for spring and

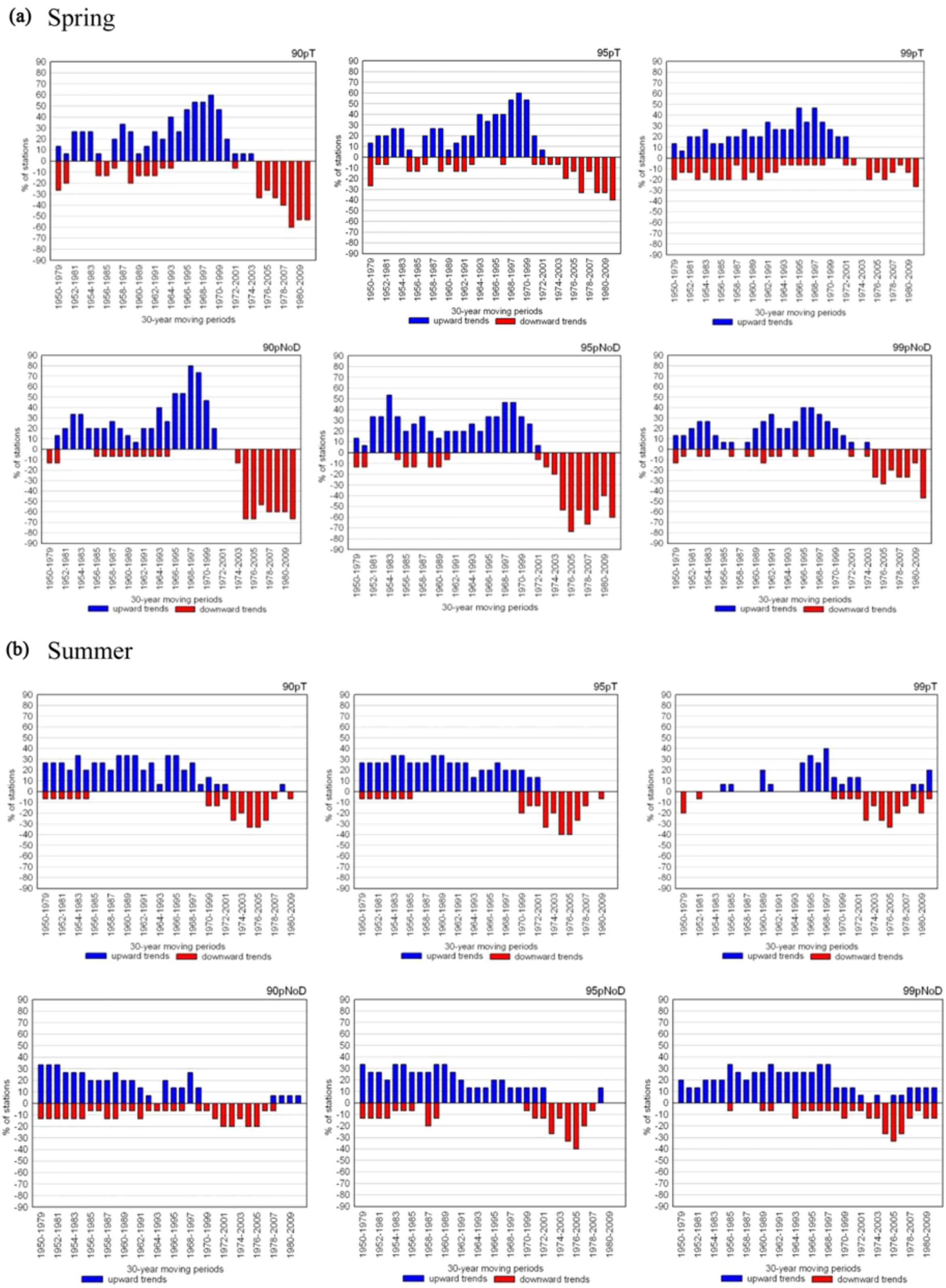


Fig. 8. Same as Fig. 6, but using Kendall's tau-based slope estimator.

summer. From the initial 30-year period to the 30-year period from 1962-1991 decreasing trends are very prominent for all indices. The highest percentage of stations with significant negative trends in the 30-year periods ranged from 33% (95pNoD) in 1959-1988 to 48% (90pNoD and 99pNoD) in 1959-1988 and 1958-1987. Decreasing trends in extreme precipitation indices began to become more frequent in the early 1950s, when positive trends started to disappear or became negligible. The extent of these negative trends decreased in the mid-1960s and remained at this reduced rate until the end of the data series. The highest positive values were observed for 90pT and 95pT (28% and 28%) in 1968-1997.

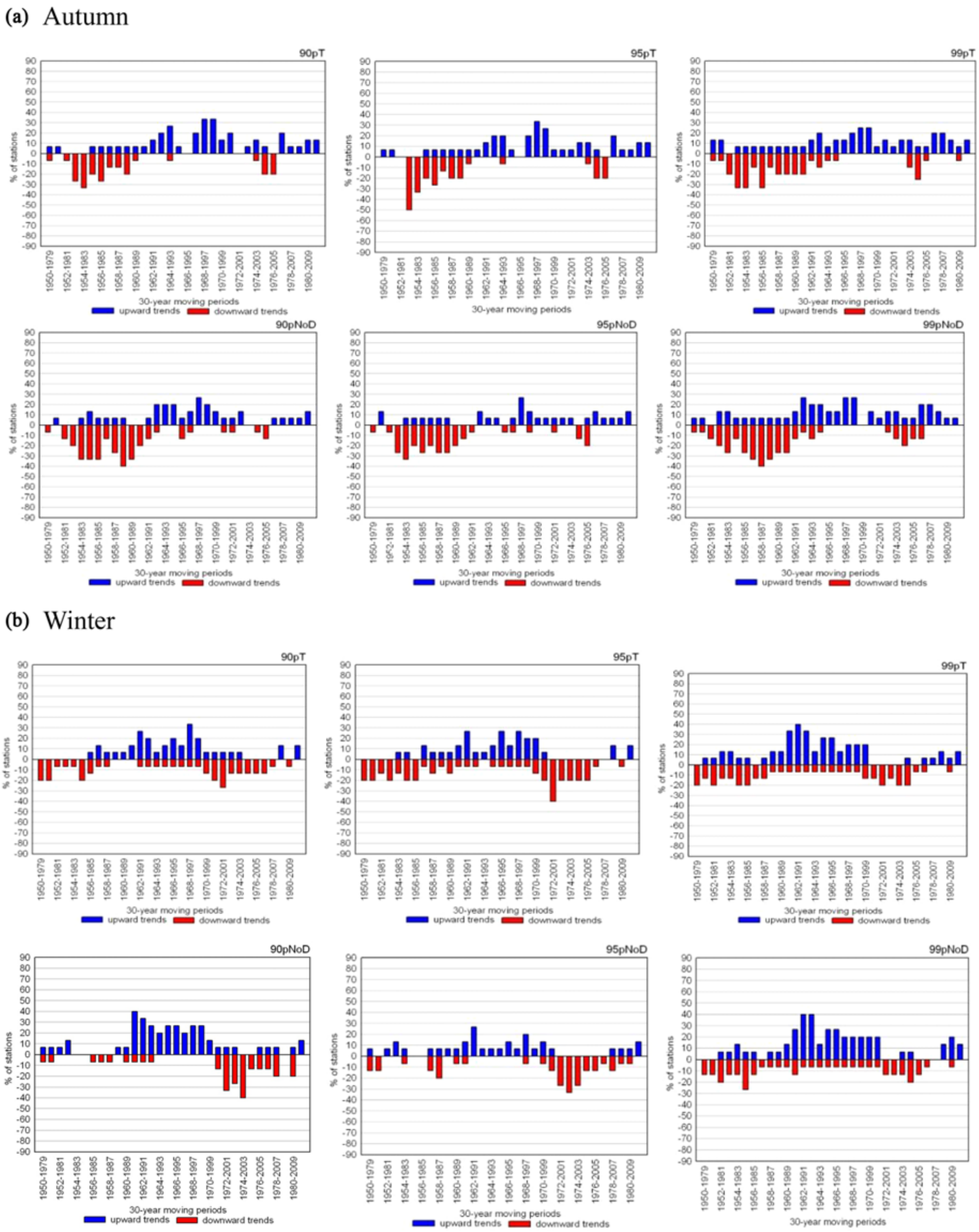


Fig. 9. Same as Fig. 7, but using Kendall's tau-based slope estimator.

Unlike the other seasons, no positive trends were observed during the winters in the 1950s for any of the indices. There is a gradual temporal change in the spatial extent of significant positive extreme precipitation trends from the early 1960s to the early 1970s. From 1971-1999 to 1981-2010, negative trends of a second phase appeared. The highest percentage of stations with significant negative trends in the 30-year periods ranged from 12% (99pT) in 1974-2003 to 68% (90pNoD and 95pNoD) in 1974-2003 and 1981-2010 (Fig. 7).

For the spring season, Kendall's tau-based slope shows considerably more decreasing trends for 99pNoD and 99pT since 1974. In the summer season, results show downward trends for 99pT during 1950-1979 to 1964-1993 (Fig. 8). However, this trend is positive during 1979-2008 to 1981-2010, when 8% of stations recorded for 99pT. The Kendall's tau-based test depicts apparent results of the calculation of 30-year periods during autumn and winter seasons. Trend direction over all 30-year periods provides visible signal of increasing/decreasing trends in autumn and winter seasons (Fig. 9).

c. Trend stability

The results of trend stability analysis are presented for every station and deliver a comprehensive picture of the spatial distribution of stations within a particular trend stability class. Results showed that all classes of trend stability occurred over the entire study period 1950-2010, but unstable trends in extreme precipitation were frequent in Pakistan (Fig. 10). Secondly, the stable trend class (25% ≤ 50%) was recorded most frequently over the study area (Table 2, Table 3). Decreasing

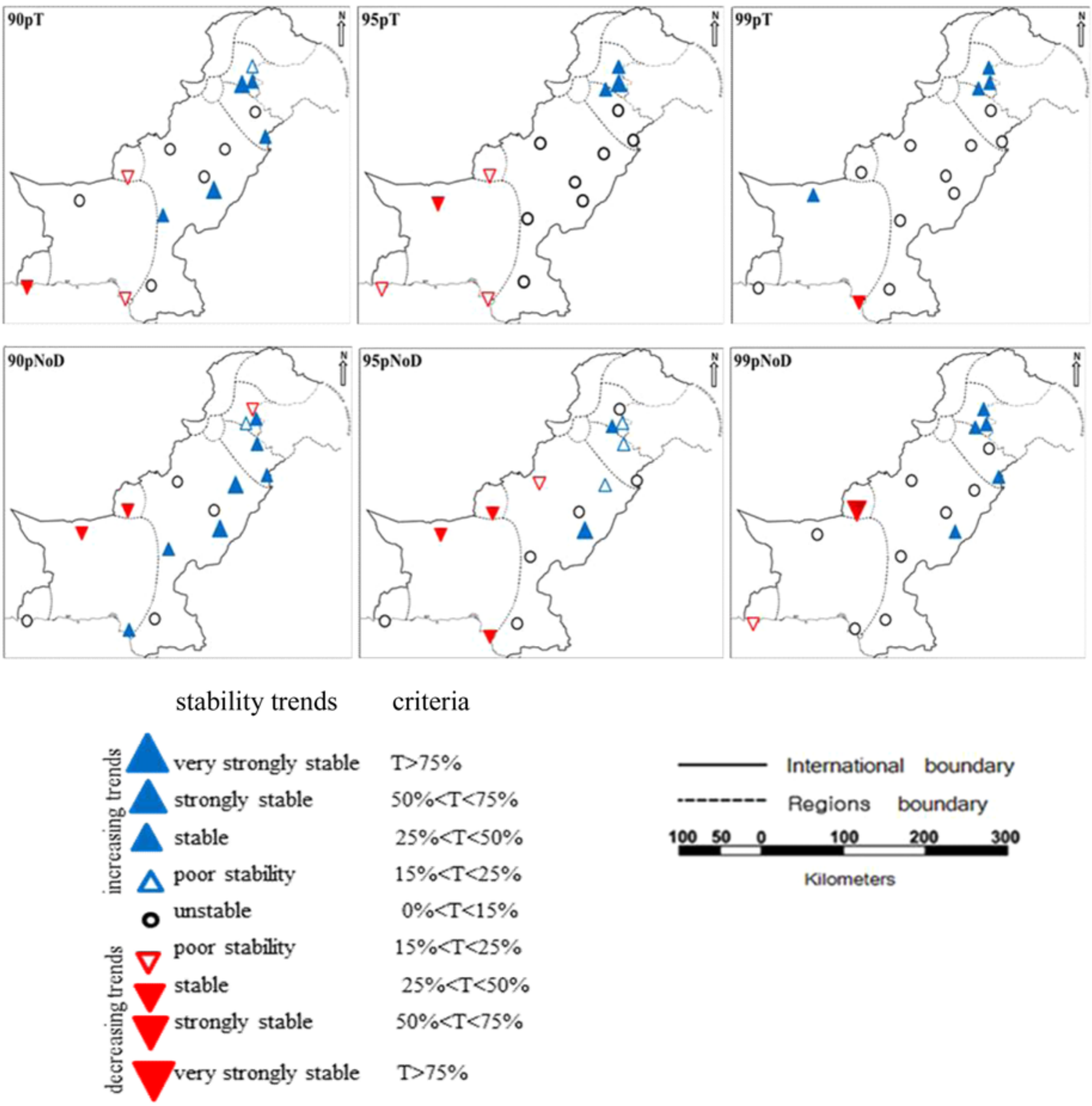


Fig. 10. Stability of statistically significant trends in annual extreme precipitation indices within 1950-2010.

Table 2. Number of stations with stable and non-stable trends in annual precipitation indices for the period 1950-2010.

	Stability	T	90pNoD	90pT	95PNoD	95pT	99pNoD	99pT	TNoDD
Upward trends	Strongly stable	50% ≤ T <7 5%	2	2	1	1	0	0	1
	Stable	25% ≤ T < 50%	5	3	1	2	5	4	3
	Poor stability	15% ≤ T < 25%	1	1	3	0	0	0	0
	Unstable trends	0% ≤ T < 15%	4	6	6	8	8	10	5
Downward trends	Poor stability	15% ≤ T < 25%	1	2	1	3	1	0	1
	Stable	25% ≤ T < 50%	2	1	3	1	0	1	2
	Strongly stable	50% ≤ T < 75%	0	0	0	0	0	0	3
	Very strongly stable	T ≥ 75%	0	0	0	0	1	0	0

Table 3. Number of stations with stable and non-stable trends in annual precipitation indices for the period 1950-2010, using Kendall's tau-based trends.

	Stability	T	90pNoD	90pT	95PNoD	95pT	99pNoD	99pT	TNoDD
Upward trends	Strongly stable	50% ≤ T<75%	2	4	1	2	1		2
	Stable	25% ≤ T < 50%	5	3	4	2	4	4	2
	Poor stability	15% ≤ T<25%	1	1	2	3	2		1
	Unstable trends	0% ≤ T < 15%	4	1	2	4	2	4	3
Downward trends	Poor stability	15% ≤ T<25%	1	3	3	1	3	4	1
	Stable	25% ≤ T < 50%	1	3	3	2	2	2	3
	Strongly stable	50% ≤ T<75%	1	0	0	1			2
	Very strongly stable	T ≥ 75%	0	0	0	0	1	1	1

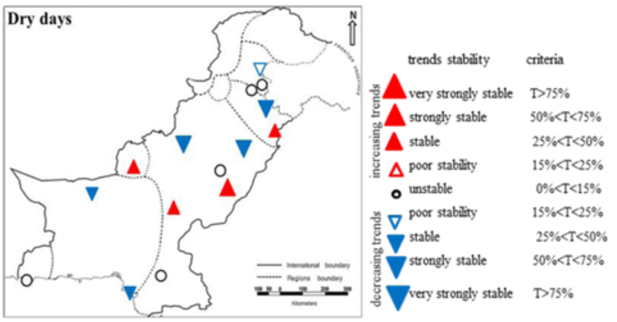


Fig. 11. Stability of statistically significant trends in annual dry days within 1950-2010.

trends featured only in the very strongly stable trends.

The spatial examination of the study area presents a very clear picture of stability trends in extreme precipitation in Pakistan. A stable increasing annual trend (all classes) is very prominent in northeastern and central Pakistan, but a stable decreasing trend (all classes) is observed in the southwestern part of the study area.

Precipitation regions 2, 5, and 6 showed stable positive trends but regions 1 and 3 showed negative trends.

In region 2, the Bahawalpur station showed strongly stable increasing trends of 53%, 65%, 68%, and 43% for 90pT, 90pNoD, 95pNoD, and 99pT, respectively, but unstable trends were observed for 95pT and 99pT. In region 6, Islamabad is the most positive station for all indices. Region 6 showed strongly stable positive trends for all indices. In regions 1 and 3, decreasing negative trends were observed for all indices; in particular, the Quetta station had the highest decreasing trend of 83% (99pNoD). With respect to dry days, the north-central and the southwestern part of the country showed stable and strongly stable decreasing trends, whereas an increasing trend was observed in the eastern and south-central part of the study area (Fig. 11).

The Kendall's tau-based test shows the clear stability of trends in extreme precipitation during the studied period. Precipitation regions 2, 5 and 6 showed stable positive trends, whereas downward trends prevailed in region 1 and 3. However, Muzafarabad and Zhob stations showed strongly stable downward trends of 50% and 40% for 95pT and 90pNoD respectively. Similar, in region 3; in particular, the Quetta station showed strongly stable decreasing trends 60%, 63%, and 84% for 90pT, 95pT and 99pT respectively (Fig. 12).

d. Seasonal trend stability

Spatial stability trends for spring in the study area were similar to the annual spatial stability trends. The country can be broadly divided into two parts according to increasing and decreasing trends. The northeast and central part of the country show stable increasing trends (all indices), but a stable decreasing trend (all indices) is observed in the southwestern part of the country. More than half of the stations (60%) showed unstable trends. Among the stable trends, positive trends usually occurred more frequently than negative trends, particularly in

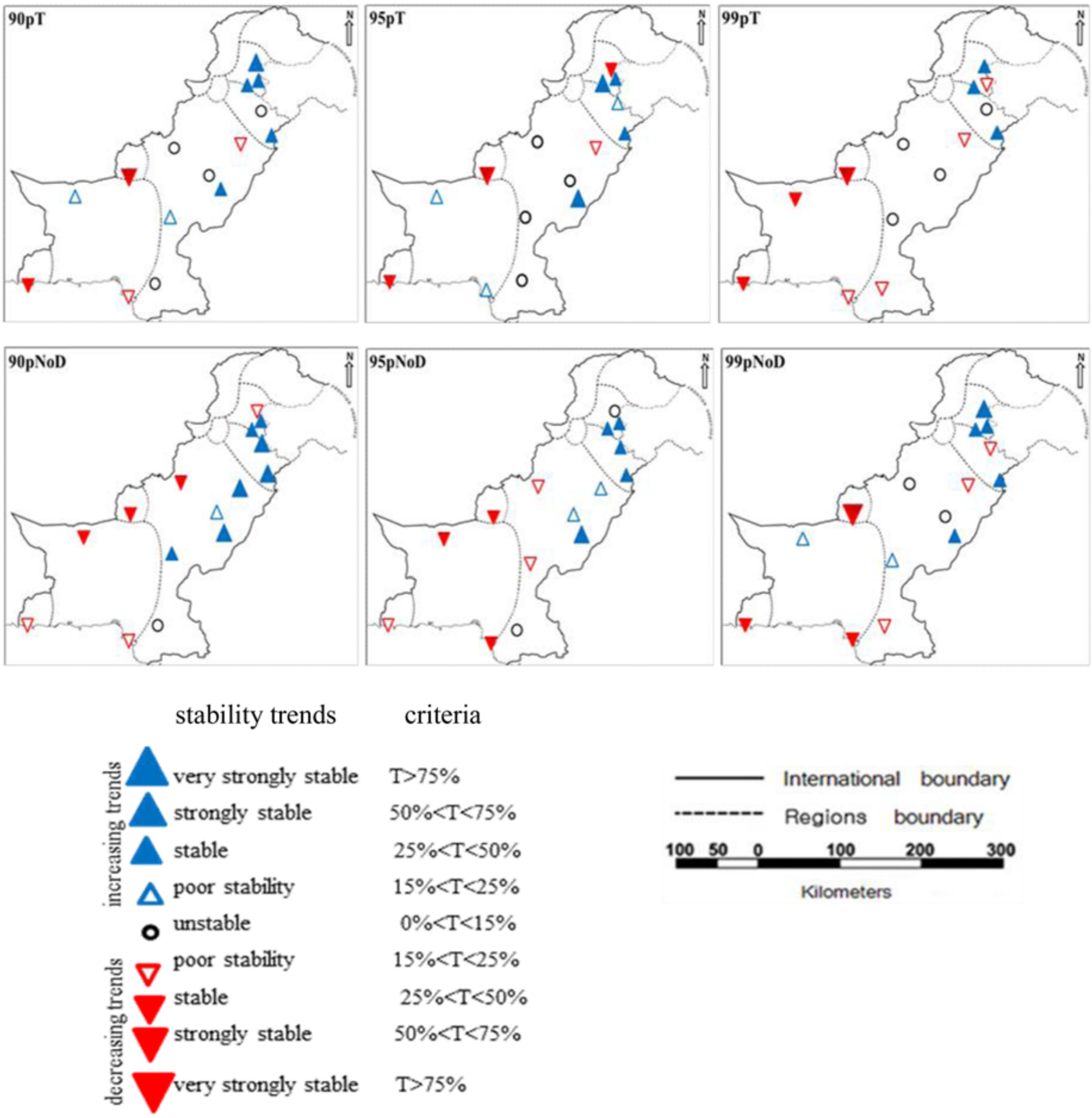


Fig. 12. Same as Fig. 10, but using Kendall's tau-based slope estimator.

regions 5, 6, and 2, for all indices. Stable was the most frequently occupied stability class for both trend directions (25%-50% of the 30-year periods showing significant trends) in all regions.

Regions 2, 5, and 6 showed stable (the 25-50% class) increasing trends and regions 1 and 3 showed stable decreasing trends. The frequency of stable positive trends was generally higher than that of stable negative trends in regions 2, 5 and 6. Nevertheless, a higher frequency of stable negative trends occurred at stations in region 5 (particularly for 90pNoD). Similarly, the frequency of stable negative trends was generally higher than that of positive trends in regions 1 and 3. The Quetta station had the most pronounced strongly stable (the class 50%-75%) decreasing trends, particularly for 95pT, 99pT, and 99pNoD. Trends in the highest stability classes appeared only at individual stations.

Of all the seasons, summer had the highest percentage of stations with stable positive extreme precipitation trends, especially in regions 2, 5, and 6, for all indices. Regions 1 and 3 had unstable (the class 0%-15%) trends. In regions 1 and 3, stable decreasing trends were generally higher than in regions 2, 5, and 6. Decreasing trends in region 1 included 34% for 90pNoD. Most stations showed unstable trends. However, the percentage of stations with stable trends (25%-50% of the 30-year trends significant) was higher than that for other seasons (Table 4). The frequency of stable summer trends, as well as their direction, is clearly differentiated between the northeastern and central regions. The stable trends in extreme precipitation

Table 4. Same as Table 2 but for seasons: spring, summer, autumn, winter.

	Stability	T	90pNoD	90pT	95pNoD	95pT	99pNoD	99pT
		Spring						
Upward trends	Strongly stable	50% ≤ T < 75%	0	0	1	0	0	0
	Stable	25% ≤ T < 50%	3	2	0	3	2	3
	Poor stability	15% ≤ T < 25%	2	2	2	1	3	2
	Unstable trends	0% ≤ T < 15%	7	9	10	9	9	8
Downward trends	Poor stability	15% ≤ T < 25%	3	1	1	1	0	1
	Stable	25% ≤ T < 50%	0	1	2	0	0	0
	Strongly stable	50% ≤ T < 75%	0	0	0	1	1	1
		Summer						
Upward tends	Stable	25% ≤ T < 50%	3	4	3	3	4	3
	Poor stability	15% ≤ T < 25%	1	0	2	2	0	1
	Unstable trends	0% ≤ T < 15%	9	10	10	10	11	10
Downward trends	Poor stability	15% ≤ T < 25%	1	1	0	0	0	1
	Stable	25% ≤ T < 50%	1	0	0	0	0	0
		Autumn						
Upward trends	Stable	25% ≤ T < 50%	0	0	0	0	1	0
	Poor stability	15% ≤ T < 25%	0	1	1	1	1	0
	Unstable trends	0% ≤ T < 15%	12	11	12	11	9	11
Downward trends	Poor stability	15% ≤ T < 25%	0	1	0	1	4	2
	Stable	25% ≤ T < 50%	3	2	2	2	0	2
		Winter						
Upward trends	Stable	25% ≤ T < 50%	3	1	0	1	1	1
	Poor stability	15% ≤ T < 25%	0	1	1	1	3	1
	Unstable trends	0% ≤ T < 15%	9	11	13	11	10	11
Downward trends	Poor stability	15% ≤ T < 25%	3	1	0	1	0	1
	Stable	25% ≤ T < 50%	0	1	0	1	0	1
	Very strongly stable	T ≥ 75%.	0	0	0	0	1	0

T - percentage of time with significant trends in extreme precipitation indices, time means number of 30-year periods. Explanation of following abbreviations; 90pT, 95pT, 99pT, 90NoD, 95NoD, 99NoD in Table 1.

indices were predominantly negative in the southwest and in southern Pakistan (for 90pT, 90pNoD, and 99pT). The trends in the highest stability classes appeared mainly in the north and in the eastern part of Pakistan in regions 2, 5, and 6 (Fig. 13).

In autumn, unstable trends in extreme precipitation in Pakistan were more frequent. In general, autumn showed stable decreasing trends for all indices in regions 1 and 3. Stable decreasing trends for all indices were observed in the southern part of region 2. However, the Bahawalpur station in region 2 showed poor stability and stable positive trends (90pT, 95pT, and 99pNoD). Regions 5 and 6 had unstable trends for all indices. Most of the stable trends in the south-central part of the study area were decreasing trends. Some of the decreasing trends were in the poor stability class (15%-25% of the 30-year periods having significant trends) in region 3 for 90pT, 95pT, and 99pT, but no station had positive trends for 90pNoD and 99pT throughout the study area.

For winter, region 3 is the top region with respect to stable (all indices) decreasing trends in extreme precipitation. During the winter season, region 3 showed a poor stability of negative trends (class 15%-25%) and stable negative trends (class 25%-50%) for 90pT, 95pT, and 99pT. The 99pNoD index showed very strongly stable decreasing trends (class +75%), whereas 95pNoD had no decreasing trends. The Bahawalpur station in region 2 showed stable (class 25%-50%) positive trends for all indices, but the Murree station in region 5 showed a poor stability (class 15%-25%) of positive trends for 90pT, 95pT, 99pT, and 99pNoD and stable (class 25%-50%) positive trends for 90pNoD. Region 6 had pronounced a poor stability (class 15%-25%) of increasing trends for 99pNoD (Fig. 14).

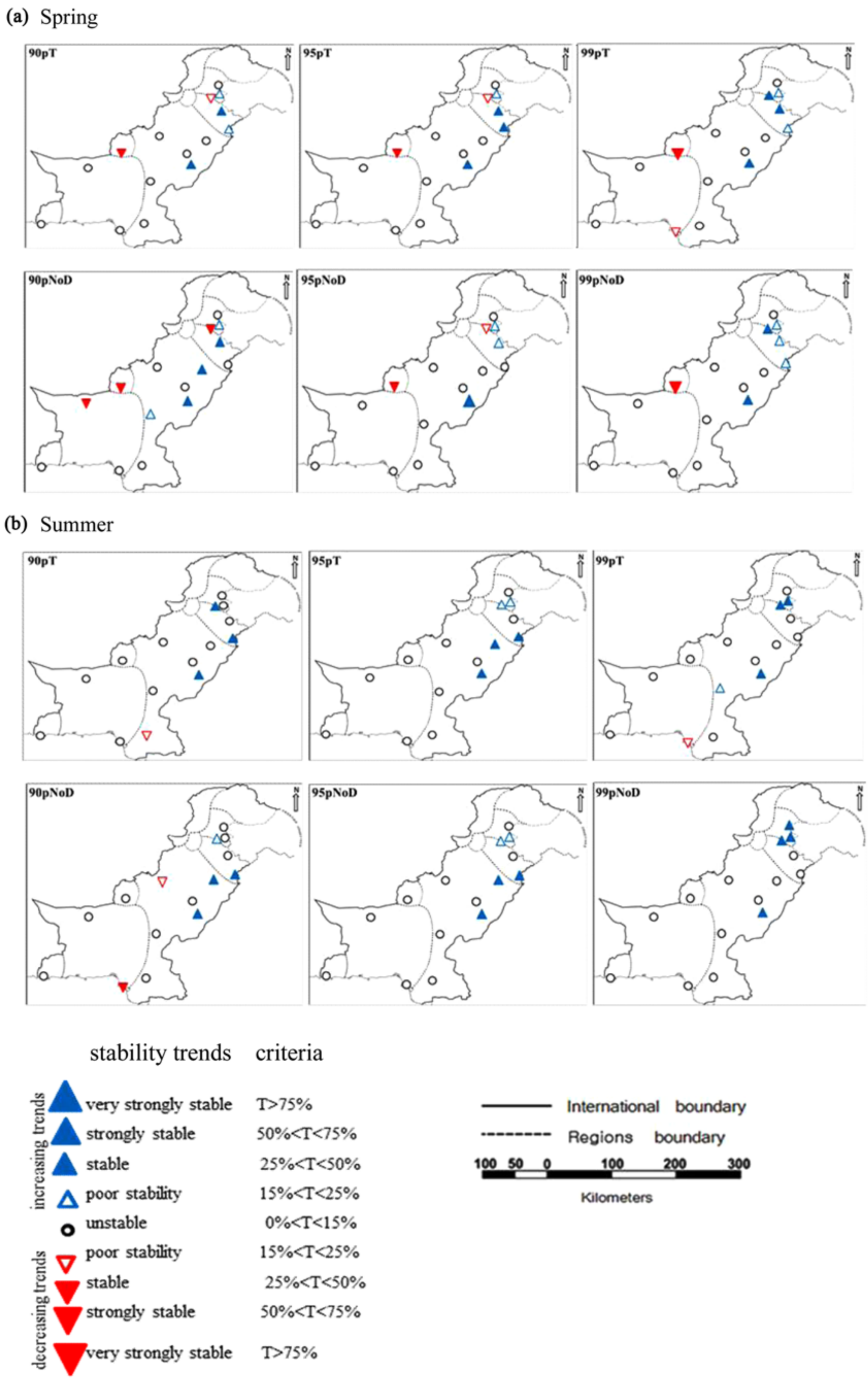


Fig. 13. Stability of statistically significant trends in extreme precipitation indices within 1950-2010 for (a) Spring and (b) Summer.

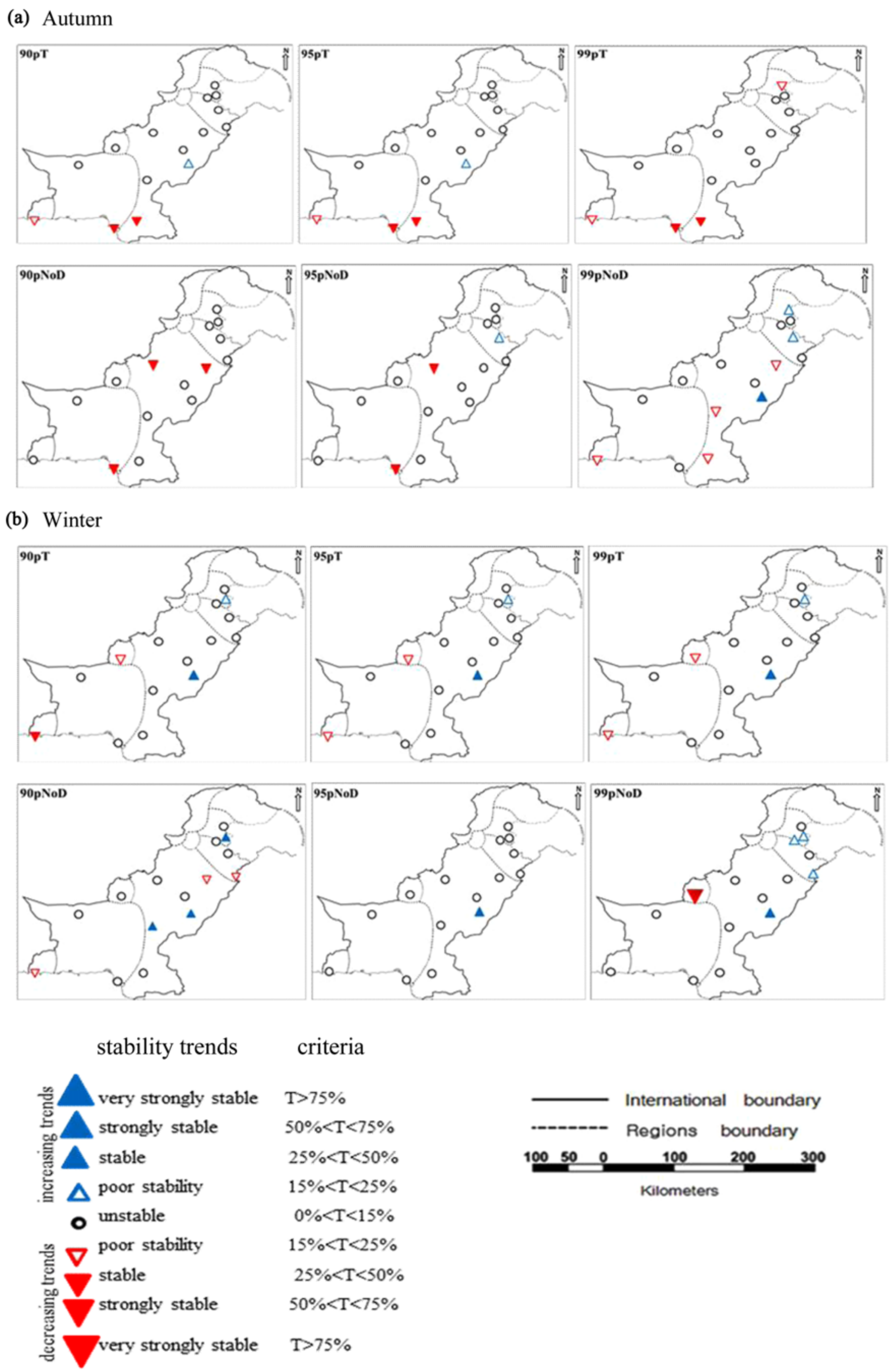


Fig. 14. Stability of statistically significant trends in extreme precipitation indices within 1950-2010 for (a) Autumn and (b) Winter.

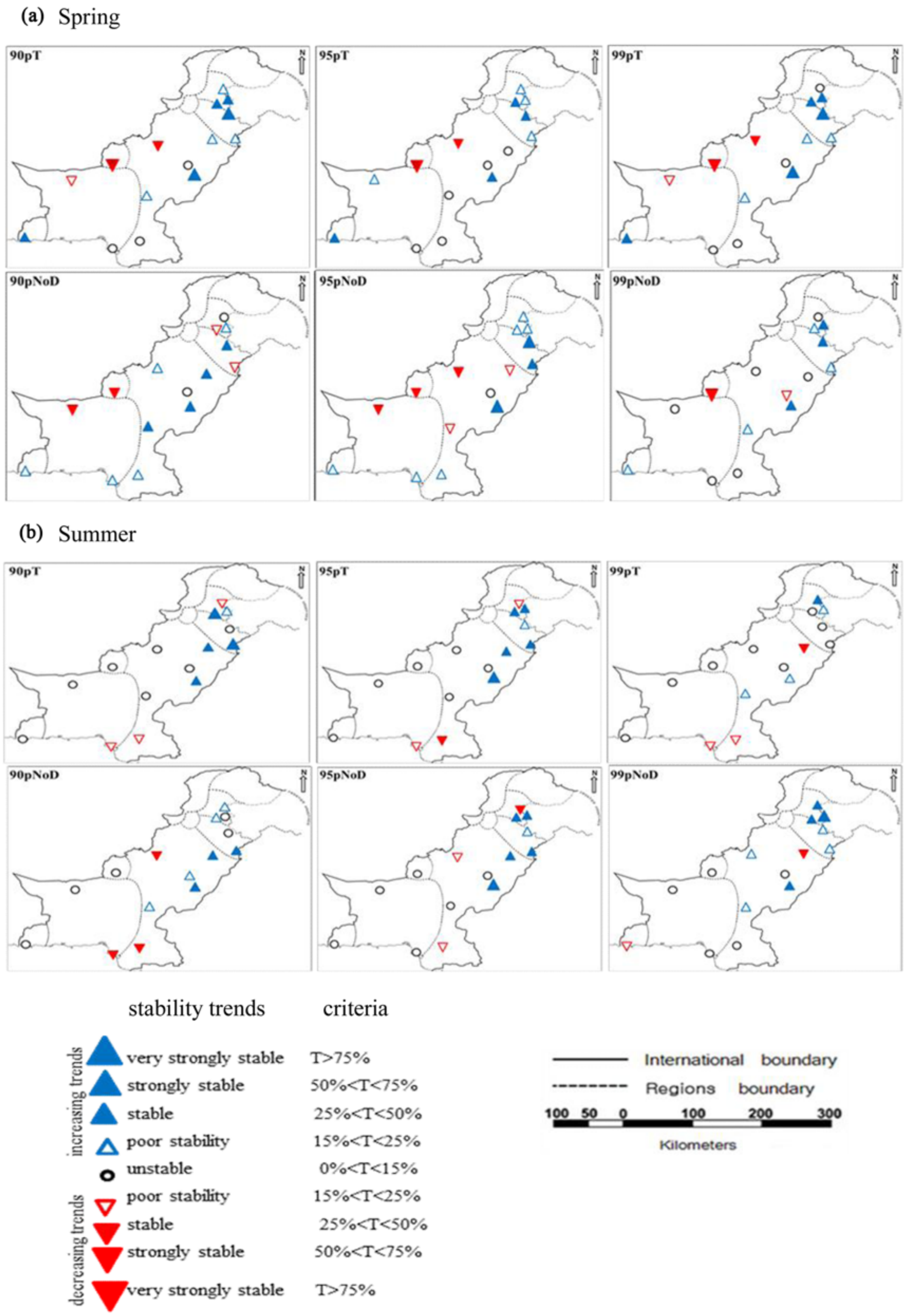


Fig. 15. Same as Fig. 13, but using Kendall's tau-based slope estimator.

According to the Kendall's tau-based test, spatial stability trends in extreme precipitation for spring and summer (Fig. 15) were similar to that annually. However, in the spring season, in region 5, particular, the Islamabad station showed a stable

Table 5. Same as Table 3 but for seasons: spring, summer, autumn, winter.

	Stability	T	90pNoD	90pT	95pNoD	95pT	99pNoD	99pT
		Spring						
Upward trends	Strongly stable	50% ≤ T < 75%		2	2			
	Stable	25% ≤ T < 50%	4	3	1	4	3	4
	Poor stability	15% ≤ T < 25%	6	4	6	4	4	1
	Unstable trends	0% ≤ T < 15%	1	3	1	5	6	5
Downward trends	Poor stability	15% ≤ T < 25%	2	1	2		1	3
	Stable	25% ≤ T < 50%	2	1	3	1		
	Strongly stable	50% ≤ T < 75%		1		1	1	1
		Summer						
Upward tends	Stable	25% ≤ T < 50%	3	4	5	5	4	1
	Poor stability	15% ≤ T < 25%	4	1	1	1	4	3
	Unstable trends	0% ≤ T < 15%	5	7	6	6	5	8
Downward trends	Poor stability	15% ≤ T < 25%		3	2	2	1	2
	Stable	25% ≤ T < 50%	3		1	1	1	1
		Autumn						
Upward trends	Stable	25% ≤ T < 50%	2	1	2	1	2	1
	Poor stability	15% ≤ T < 25%	1	3		2	2	4
	Unstable trends	0% ≤ T < 15%	8	9	9	10	6	6
Downward trends	Poor stability	15% ≤ T < 25%	1	2	2	1	3	2
	Stable	25% ≤ T < 50%	3		2	1	2	2
		Winter						
Upward trends	Stable	25% ≤ T < 50%	3	1	1	1	2	2
	Poor stability	15% ≤ T < 25%	3	1		1	4	4
	Unstable trends	0% ≤ T < 15%	4	10	10	9	7	5
Downward trends	Poor stability	15% ≤ T < 25%	4	1	3	2	2	3
	Stable	25% ≤ T < 50%	1	1	1	1		
	Very strongly stable	T ≥ 75%	0	1	0	1	0	1

T - percentage of time with significant trends in extreme precipitation indices, time means number of 30-year periods. Explanation of following abbreviations; 90pT, 95pT, 99pT, 90NoD, 95NoD, 99NoD in Table 1.

upward trend and a strong stable upward trend for 95pT and 95pNoD respectively. The summer season had the highest percentage of stations with stable upward extreme precipitation trends, which were observed mainly in the north and in the eastern part of the country. However, trend stability, in particular stable upward class (25%-50% of the 30-year significant trends) was higher than that for the other seasons (Table 4, Table 5). In region 5, decreasing trends were observed, and in particular, the Muzafarabad station showed a poor stability of downward trends and stable downward trends for 95pT and 95pNoD, respectively. Figure 16 indicates that extreme precipitation was more frequent in the autumn and the winter seasons. However, in winter, significant downward (strongly stable and very strongly stable) trends were prominent for 90pT, 95pT and 99pT categories, respectively. Similarly, in the autumn season, extreme precipitation events have significant upward trends for 90pT, 95pT and 99pT, in particular, in the north and in the eastern part of Pakistan.

5. Conclusions

Producing a reliable analysis of long-term changes in extreme precipitation is a complex task. Several problems, such as a lack of data homogeneity, changes and installation of instruments, and the lack of a long-term data series, contribute to the difficulties associated with this type of study. In practice, changes in extreme precipitation are noteworthy trends and have very direct consequences, especially in terms of the risk of flooding and other changes affecting river navigation and engineering structures, such as urban drains, bridges, dams,

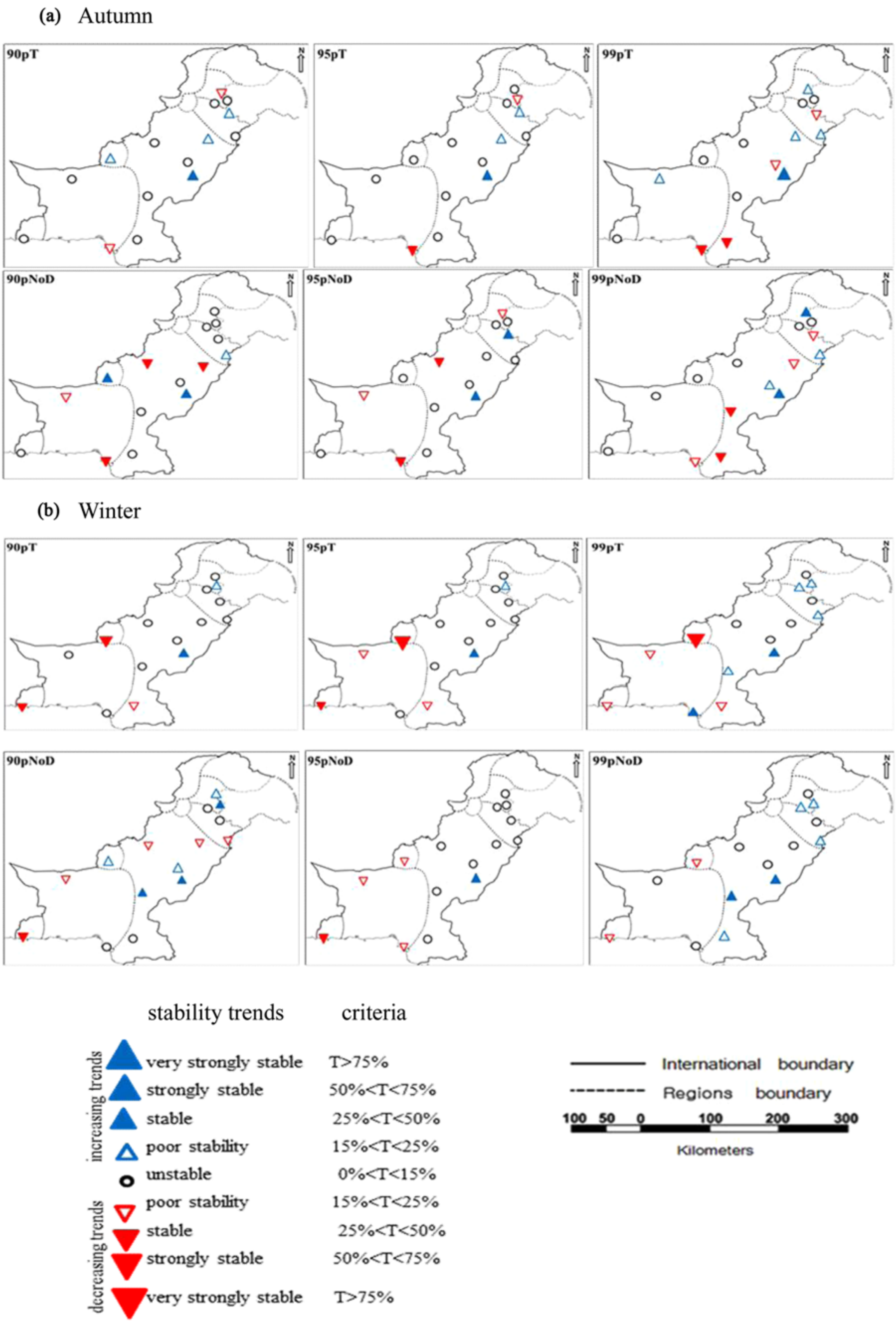


Fig. 16. Same as Fig. 14, but using Kendall's tau-based slope estimator.

and roads.

A study of the daily precipitation dataset for Pakistan from 15 weather stations over a period of 61 years was undertaken in order to investigate changes in extreme precipitation which may have occurred. The research addressed extreme seasonal and annual precipitation events as their ≥ 90th, 95th, and 99th percentiles, as well as the number of days with precipitation of ≥ 90th, 95th, and 99th percentiles of daily precipitation amounts. The results of this research confirm the large degree of spatial variability in heavy precipitation within the data. Furthermore, a distinct seasonality in spatial and temporal patterns of the trends were revealed, with respect to statistical significance and direction. Generally, trend direction was specified by trend stability analysis. Seasonal differences in the number and direction of statistically significant trends for the seven extreme precipitation indices were investigated. This method allows for the identification of the index and the season with the most significant changes in extreme precipitation.

Considering spatial patterns, positive trends dominated large areas of Pakistan. Over the long term, the 30-year periods of 1950-1979 and 1970-1999 had upward trends for 90pNoD, 90pT, 95pNoD, and 99pNoD, whereas 95pT and 99pT had slightly increasing stable trends. However, the 30-year period 1981-2010 showed a clear downward trend for 90pNoD, 90pT, 95pNoD, and 99pNoD and a clear stable increasing trend for 95pT and 99pT. A distinct spatial differentiation appeared in the prevailing trend directions between the northern and southwestern parts of the study area. In all seasons, increasing trends in extreme precipitation dominated in northeastern Pakistan, whereas opposite trends prevailed in the southwestern part of the country. This pattern of increasing trends appeared prominently in spring and summer, and dominated the initial 30-year periods of the data series, whereas the downward trends were common in the 30-year periods from 1972. In autumn and winter, a stable decrease in extreme precipitation indices was observed mainly in the southwestern part of the country. Very strongly stable trends were recorded during winter in western Pakistan. However, summer was characterized by the most pronounced temporal changes in the percentage of significant positive trends. The strongest negative trends were observed during the winter season, particularly in the west.

The impact of rainfall on agriculture is extremely important in Pakistan, because it is an area of high temperature, dry climate, and thunderstorms, which affect the production of crops. Agriculture performance in Pakistan has been unsatisfactory due to a number of factors, such as the traditional methods of cultivation, but also due to the infrequent occurrence of rain, as well as the high frequency of extreme weather events, including flooding and drought. Furthermore, the life of a farmer, whether based on subsistence or cash crops, is hard in both mountainous areas and lower catchments. Furthering our knowledge of the relationship between changes in extreme precipitation and agricultural yields creates a new horizon for research.

In the present era, weather records, the analysis of long-term observations of climatic information are essential to economists, agricultural scientists and other technical specialists. For more immediate use, however, observations from the world network of weather stations are exchanged between the countries of the world by high-speed telecommunication systems. It is therefore important that more research should be performed, keeping the fact that Pakistan is a populated country, it is essential to study its climatic elements such as extreme precipitation in connection to floods, agriculture, urban sewerage, infrastructure, such as drains, bridges, roads and dams. Hence, it is obvious that climate change, either of a global or regional nature, may lead to changes in spatial and temporal extreme precipitation, with significant consequences for water resources and water management practices in Pakistan.

The present research provides knowledge of extreme precipitation trends in Pakistan. Firstly, the changing trends in annual extreme precipitation, as well as the number of precipitation days and seasonal extreme precipitation days have been clarified in the data series. Additionally, this study provides useful information to policymakers and the community for future general planning, the development of agriculture, and especially the future forecasting of floods, a frequently occurring natural disaster which Pakistan faces.

Acknowledgements. The data used in this study was obtained from the Pakistan Meteorological Department (PMD), Islamabad, Pakistan. The authors wish to thank the anonymous reviewers for their useful comments.

Edited by: Tianjun Zhou

REFERENCES

Afzal, M., and Q. Zaman, 2010: Case study: Heavy rainfall events over Lai Nullah catchment area. *Pakistan J. Meteor.,* **6**(12), 39-48.

Aziz, A., and S. Tanaka, 2011: Regional parameterization and applicability of intergrated flood analysis system (IFAS) for flood forcasting of upper-middle Indus river. *Pakistan J. Meteor.,* **8**(15), 21-38.

Brunetti, M., M. Colacino, M. Maugeri, and T. Nanni, 2001: Trends in the daily intensity of precipitation in Italy from 1951 to 1996. *Int. J. Climatol.,* **21**(3), 299-316.

______, M. Maugeri, and T. Nanni, 2001: Changes in total precipitation, rainy days and extreme events in Northeastern Italy. *Int. J. Climatol.,* **21**(7), 861-871.

Burt, T. P., and E. J. S. Ferranti, 2010: Changing patterns of heavy rainfall in upland areas: a case study from northern England. *Int. J. Climatol.,* DOI: 10.1002/joc.2287.

Caloiero, T., R. Coscarelli, E. Ferrari, and M. Mancini, 2011: Trend detection of annual and seasonal rainfall in Calabria (Southern Italy). *Int. J. Climatol.,* DOI: 10.1002/joc.2055.

Deshpande, N. R., A. Kulkarni, and K. K. Kumar, 2011: Characteristic features of hourly rainfall in India. *Int. J. Climatol.,* DOI: 10.1002/joc.2375.

Dravitzki, S., and J. Mcgregor, 2010: Extreme precipitation of the Waikato region, New Zealand. *Int. J. Climatol.,* DOI: 10.1002/joc.2189.

Field, A., 2005: *Discovering Statistics Using SPSS.* 2nd Edition, SAGE

Publication, London, 131 pp.
Frei, C., and C. Schar, 2000: Detection probability of trends in rare events: theory and application to heavy precipitation in the Alpine region. *J. Climate.,* **14**(7), 1568-1584.
Gillies, R. R., S. Y. Wang, and W. R. Huang, 2011: Observational and supportive modeling analysis of winter precipitation change in China over the last half century. *Int. J. Climatol.,* DOI: 10.1002/joc.2303.
Hassan, M. A., S. Haider, and U. Kalim, 2011: Diagnostic study of heavy downpour in the central part of *Pakistan J. Meteor.,* **7**(13), 53-61.
Harju, A. B., A. Grimvall, and C. N. Bromssen, 2010: A test for network-wide trends in rainfall extremes. *Int. J. Climatol.,* DOI: 10.1002/joc. 2263.
Haylick, M., and N. Nicholls, 2000: Trends in extreme rainfall indices for an updated high quality data set for Australia, 1910-1998. *Int. J. Climatol.,* **20**(13), 1533-1541.
Hussain, M. S., and S. Lee, 2009: A classification of rainfall regions in Pakistan. *J. Korean Geographical Soc.,* **44**(5), 605-623.
Iwasaki, H., 2010: Recent positive trend in heavy rainfall in eastern Japan and its relation with variations in atmospheric moisture. *Int. J. Climatol.,* DOI: 10.1002/joc.2269.
Kazi, S. A., 1951: Climatic regions of West Pakistan. *Pakistan Geographical Review,* **6**(1), 1-22.
Khan, J. A., 1993: *The Climate of Pakistan.* Rehber Publishers, Karachi.
Kunkel, K.E., 2003: North American trends in extreme precipitation. *Nat. Hazards* **29**(2), 291-305.
Lee, S. H., E. K. Kim, and I. H. Heo, 2011: A study on variability of extreme precipitation by basin in South Korea. *J. Korean Geographical Soc.,* **17**(5), 505-520.
Li, J., J. Feng, and Y. Li, 2011: A possible cause of decreasing summer rainfall in northeast Australia. *Int. J. Climatol.,* DOI: 10.1002/joc.2328.
Lupikasza, E., 2010: Spatial and temporal variability of extreme precipitation in Poland in the period 1951-2006. *Int. J. Climatol.,* DOI: 10.1002/joc.1950.
Lupikasza, E. B., S. Hansel, and J. Matschullat, 2010: Regional and seasonal variability of extreme precipitation trends in southern Poland and central-eastern Germany. *Int. J. Climatol.,* DOI: 10.1002/joc.2229.
Mason, S. J., and A. M. Joubert, 1997: Simulated changes in extreme rainfall over Southern Africa. *Int. J. Climatol.,* **17**(3), 291-301.
______, P. Waylen, G. M. Mimmack, B. Rajaratnam, and J. M. Harrison, 1999: Changes in extreme rainfall events in South Africa. *Climatic Change,* **41**(2), 249-257.
Nastos, P. T., and C. S. Zerefos, 2007: On extreme daily precipitation totals at Athens, Greece. *Advances in Geosciences,* **10**, 59-66.
______, and ______, 2008: Decadal changes in extreme daily precipitation in Greece. *Adv. in Geosci.,* **16**, 55-62.
Naumann, G., M. P. Llano, and W. M. Vergas, 2010: Climatology of the annual maximum daily precipitation in the La Plata Basin. *Int. J. Climatol.,* DOI: 10.1002/joc.2265.
Park, J. S,. H. S. Kang, Y. S. Lee, and M. K. Kim, 2010: Changes in the extreme daily rainfall in South Korea. *Int. J. Climatol.,* DOI: 10.1002/joc.2236.
Raj, P. P. N., and P. A. Azeez, 2010: Trend analysis of rainfall in Bharathapuzha River basin, Kerala, India. *Int. J. Climatol.,* DOI: 10.1002/joc.2283.
Ravadekar, J. V., and B. Preethi, 2010: Statistical analysis of the relationship between summer monsoon precipitation extremes and foodgrain yield over India. *Int. J. Climatol.,* DOI: 10.1002/joc.2282.
Raziei, T., A. Mofidi, J. A. Santos, and I. Bordi, 2011: Spatial patterns and regimes of daily precipitation in Iran in relation to largr-scale atmospheric circulation. *Int. J. Climatol.,* DOI: 10.1002/joc.2347.
Roy, S. S., and J. R. C. Balling, 2004: Trends in extreme daily precipitation indices in India. *Int. J. Climatol.,* **24**(4), 457-466.
Samba, G., and D. Nganga, 2011: Rainfall variability in Congo-Brazzaville: 1932-2007. *Int. J. Climatol.,* DOI: 10.1002/joc.2311.
Schmidli, J., and C. Frei, 2005: Trends of heavy precipitation and wet and dry spells in Switzerland during the 20^{th} century. *Int. J. Climatol.,* **25**(6), 753-771.
Shirazi, S.A., 2006: Impacts of spatio-temporal trends and anomalies of surface air temperature over the Punjab. *Geographical papers,* **1**(1), 22-32.
Smadi, M. M., and A. Zghol, 2006: A sudden change in rainfall characteristics in Amman, Jordan during the mid 1950s. *Amer. J. Environ. Sci.,* **2**(3), 84-91.
Svensson, C., and D. Jakob, 2002: Diurnal and seasonal characteristics of precipitation at upland site in Scotland. *Int. J. Climatol.,* **22**(5), 587-598.
Toros, H., 2011: Spatio-temporal precipitation change assessments over Turkey. *Int. J. Climatol.,* DOI: 10.1002/joc. 2353.
Turkes, M., 1996: Spatial and temporal analysis of annual rainfall variation in Turkey. *Int. J. Climatol.,* **16**(9), 1057-1076.
Zhai, P., Zhang, X. Wan, H., and Pan, X., 2005: Trends in total precipitation and frequency of daily precipitation extremes over China. *J. Climate.,* **18**(7), 1096-1108.
Zhang, G. H., M. A. Nearing and B. Y. Liu, 2005: Potential effects of climate changes on rainfall erosivity in the Yellow river basin of China. *Amer. Soc. Agric. Eng.,* **48**(2), 511-517.
Zolina, O., C. Simmer, A. Kapala, S. Bachner, S. Guley, and H. Maechel, 2008: Seasonal dependant changes of precipitation extremes over Germany since 1950 from dense observational network, *J. Geophys. Res.,* **113**(6), 1-17.