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REVIEW ARTICLE

Spatial patterns and trends of daily rainfall regime in Peninsular Malaysia during the southwest and northeast monsoons: 1975–2004

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Abstract This study focuses on describing the patterns and trends of five selected rainfall indices in Peninsular Malaysia, based on daily rainfall data from 1975 to 2004. Five rainfall indices based on two main seasons, the northeast and southwest monsoons, were analyzed: total rainfall, frequency of wet days, rainfall intensity, frequency of wet days (extreme frequency), and rainfall intensity (extreme intensity) exceeding the long-term mean 95th percentile. The findings indicated that the eastern areas of the Peninsula were strongly influenced by the northeast monsoon, while the southwest monsoon had the greatest impact on the western part of the Peninsula, particularly the northwest. In studying the trends of these rainfall indices, the non-parametric Mann–Kendall test was used. The serial correlation and cross-correlation structure of the data were accounted for in determining the significance of the Mann–Kendall test results. It was found that there were differences in trend patterns over the Peninsula during both seasons, with a decrease in total rainfall and a significant decrease in frequency of wet days leading to a significant increase in rainfall intensity over the Peninsula, except in eastern areas, during the southwest monsoon. In contrast, a trend of significantly increasing total rainfall and an increase in frequencies of extreme rainfall events during the northeast monsoon caused a significantly increasing trend in rainfall intensity over the Peninsula to be observed. However, no significant trend was observed with respect to extreme intensity during both monsoons over the Peninsula. The findings of this study suggest that rainfall patterns in Peninsular Malaysia are very much affected by the northeast monsoon, based on the larger magnitude of changes observed in the rainfall indices.

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1 Introduction

Understanding rainfall characteristics is crucial, particularly with regard to managing water resources becoming increasingly scarce due to rapid population growth and economic development. Studies on rainfall behavior have attracted much attention from scientists throughout the world, such as those carried out by Lana et al. (2004), Martinez et al. (2007), Aravena and Luckman (2008), Sen Roy (2009) and Turkes et al. (2008).

In studying rainfall behavior, results are found to vary between regions. Some studies describe significant positive trends in rainfall intensity, such as analyses from the United States (Frich et al. 2002; Karl and Knight 1998), northern and central Italy (Brunetti et al. 2000, 2001), eastern and northeastern Australia (Suppiah and Hennessey 1998; Plummer et al. 1999), and South Africa (Mason et al. 1999), with results indicating an increasing trend occurrence during heavy and extreme rainfall events. Karl and Knight (1998) found a statistically significant increase in rainfall greater than 50.8 mm/day in the United States from the 1910s to the 1990s. Similarly, Suppiah and Hennessey (1998) observed an increasing trend in heavy daily rainfall (greater than the 90th and 95th percentiles) in Australia, both during the summer and winter half-years. On a global scale, Frich et al. (2002) found a significant increase in both the amount of extreme rainfall derived from wet spells and the number of heavy rainfall events during the second half of the twentieth century.

On the other hand, a decrease in total rainfall has been observed in other parts of the world, such as in Basilicata (southern Italy) (Piccarreta et al. 2004), Nigeria (Hess et al. 1995), northern China (Gong et al. 2004), and Sicily (Cannarozzo et al. 2006). Hess et al. (1995) found that the main reason for the decrease in total rainfall was a reduction of 6–25 days in the number of rainy days during the rainy season. Similarly, Brunetti et al. (2000) showed that as annual rainfall and number of rainy days per year decreased, rainfall intensity increased. However, it has been observed that the tendency in most countries experiencing either a significant increase or decrease in total rainfall is directly related to changes in the amount of rainfall during heavy and extreme events (Easterling et al. 2000). In most cases, there have been changes in the same direction (increase or decrease) in both total rainfall and the frequency of heavy rainfall events.

The relationship between increase in total rainfall and frequency of heavy rain events was studied by Groisman et al. (1999), using a gamma distribution method. In general, their results showed that as mean rainfall increased, a disproportionate increase in heavy rainfall was also expected. However, in some cases, such as in Siberia, an increase in heavy rainfall was observed in conjunction with a decrease in total rainfall (Groisman et al. 1999).

With regard to Southeast Asia, annual rainfall decreased between 1961 and 1998, with the number of rainy days decreasing significantly throughout most Southeast Asian countries (Manton et al. 2001). According to Trenberth and Hoar (1997), this decrease in annual rainfall is associated with El Niño events which have affected these regions since the mid-1970s. As a result of these events, Malaysia has experienced numerous droughts, with the most significant occurring during 1982/1983 and 1997/1998, causing an extensive impact on both the environment and human activity across the whole nation. Some parts were also threatened by extensive wild forest fires due to the prolonged dry weather conditions. Apart from being affected by drought, Malaysia has also suffered from extreme rainfall events. For example, an extreme rainfall event caused severe flooding over the east coast of Peninsular Malaysia from 9 to 11 December 2004 (Juneng et al. 2007). In addition, due to the cold surges of the northeast monsoon, abnormally heavy rainfall occurred in the southern part of Peninsular Malaysia for several days in late December 2006 and in the middle of January 2007, causing massive floods in the region (Malaysian Met. Department 2006, 2007). Consequently, the behavior of daily rainfall, such as the frequency of wet days, rainfall intensity and the length of wet and dry spells, has been questioned and raised concerns amongst researchers. For that reason, the analysis of observed rainfall records needs to be carried out in order to determine the patterns of rainfall indices and to investigate the significance of rainfall trends.

The objective of this study is to trace the behavior of seasonal rainfall in Peninsular Malaysia over the past 30 years. This includes describing the spatial distribution of rainfall indices such as total rainfall, frequency of wet days, rainfall intensity and two extreme rainfall indices; frequency of wet days and intensity during the heavy rainfall event. In addition, trend analysis has been conducted to determine any possibly significant trend in the seasonal rainfall indices that could represent rainfall variability in Peninsular Malaysia.

2 Study area

Peninsular Malaysia is situated in the tropics at between 1° and 7° north of the equator. In general, the country experiences a wet and humid tropical climate throughout the year, characterized by high annual rainfall, humidity, and temperature. Peninsular Malaysia has a uniform temperature of 25.5–32°C throughout the year. Normally, annual rainfall is between 2,000 and 4,000 mm, while the annual number of wet days ranges from 150 to 200.

The climate of Peninsular Malaysia is described by four monsoons, or more precisely two monsoons separated by two inter-monsoons. In this study, the southwest monsoon (SWM) occurs from May to August with the northeast monsoon (NEM) from November to February. In addition, the period of first inter-monsoon (FIM) refers to the months from March to April and the second inter-monsoon (SIM) from September to October. In Peninsular Malaysia, the Main Range Mountains, known locally as Banjaran Titiwangsa, run southward from the Malaysia–Thai border in the north, spanning a distance of 483 km and separating the eastern and western parts of the Peninsula. During the NEM season, exposed areas in the eastern part of the Peninsula receive heavy rainfall. In contrast, areas sheltered by the Main Range, as shown in Fig. 1, are more or less free from its influence.

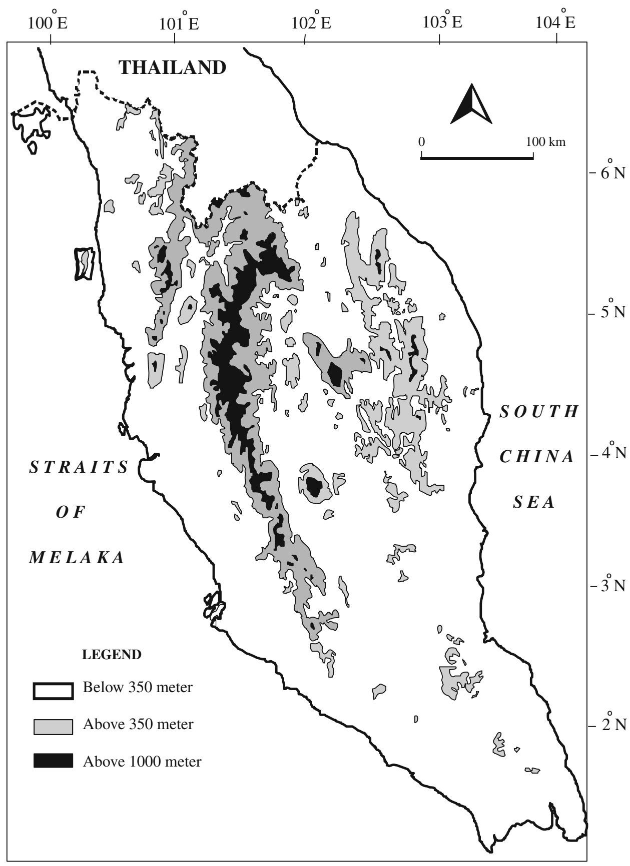

Fig. 1 Physical map of Peninsular Malaysia

3 Data

Daily rainfall data from 50 rain gauge stations were obtained from the Malaysian Meteorological and Drainage and Irrigation Departments for the period of 1975–2004. Based on rainfall distribution, Dale (1959) delineated five rainfall regions in Peninsular Malaysia: northwest, west, Port Dickson-Muar coast, southwest, and east (Lim and Azizan 2004). In this study, the stations located on the Port Dickson-Muar coast were combined with those in the southwest region, due to the very limited number of stations available in the former. A list of the 50 stations is provided in Table 1 and their respective locations in Fig. 2.

In this study, the quality of rainfall data was checked by testing for any missing values and data homogeneity. Less than 10% of daily rainfall values were found to be missing for the period studied. The revised spatial weighting methods discussed by Suhaila et al. (2008) were used to estimate and replace these missing values. Finally, the homogeneity of the rainfall series was checked by using the four approaches of Wijngaard et al. (2003): the standard normal homogeneity test, Buishand range test, Pettitt test, and Von Neumann ratio test.

Table 1 The list of 50 rain gauge stations with their geographical coordinates

Code	Name of the stations	Latitude	Longitude
Southwest			
S01	Johor Bahru	1.47	103.75
S02	Tampok	1.63	103.20
S03	Senai	1.63′	103.67
S04	Kota Tinggi	1.76	103.72
S05	Batu Pahat	1.87	102.98
S06	Sembrong	1.88	103.05
S07	Separap	1.92	102.88
S08	Kluang	2.02	103.32
S09	Tangkak	2.25	102.57
S10	Malacca	2.27	102.25
S11	Sungai Udang	2.29	102.13
East			
E01	Mersing	2.45	103.83
E02	Endau	2.59	103.67
E03	Bukit Ibam	3.17	102.98
E04	Pekan	3.56	103.36
E05	Kuantan	3.78	103.22
E06	Kangsar	3.90	102.43
E07	Kemaman	4.23	103.42
E08	Dungun	4.76	103.42
E09	Menerong	4.94	103.06
E10	Kuala Terengganu	5.32	103.13
E11	To' Uban	5.97	102.14
E12	Kota Bharu	6.17	102.28
West			
W01	Port Dickson	2.53	101.80
W02	Seremban	2.74	101.96
W03	Sungai Lui Halt	3.08	102.37
W04	Petaling Jaya	3.10	101.65
W05	Subang	3.12	101.55
W06	Ampang	3.16	101.75
W07	Genting Kelang	3.24	101.75
W08	Gombak	3.27	101.73
W09	Bagan Terap	3.73	101.08
W10	Chui Chak	4.05	101.17
W11	Sitiawan	4.22	100.70
W12	Ldg Boh	4.45	101.43
W13	Ipoh	4.57	101.10
W14	Gua Musang	4.88	101.97
W15	Batu Kurau	4.98	100.80
W16	Alor Pongsu	5.05	100.59
W17	Selama	5.14	100.70
Northwest			
N01	Bayan Lepas	5.30	100.27
N02	Bukit Berapit	5.38	100.48
N03	Air Itam	5.48	100.27
N04	Bukit Bendera	5.42	100.27

Table 1 continued

Code	Name of the stations	Latitude	Longitude
N05	Bumbong Lima	5.56	100.44
N06	Alor Star	6.20	100.40
N07	Ampang Pedu	6.24	100.77
N08	Katong	6.45	100.19
N09	Abi	6.51	100.18
N10	Bukit Temiang	6.54	100.23

To account for seasonal differences between the SWM and NEM seasons, daily rainfall data have been segregated into two corresponding groups. SWM season data includes that from each May–August period, while NEM season daily rainfall data runs from November to February.

4 Methodology

The statistical significance of trends was assessed using the non-parametric Mann–Kendall (MK) test, also known as Kendall's tau test (Mann 1945; Kendall 1975). This test has been applied in many studies to identify whether monotonic trends exist in hydro-meteorological data, such as temperature, rainfall, and streamflow. The advantage of the MK test over conventional trend tests, for example, the linear regression test, is due to the fact that it does not require any prior assumption of the data; in linear regression, the data is assumed to be normally distributed. It is also possible to obtain a non-parametric estimate for the magnitude of the slope of the trend, as proposed by Theil (1950) and Sen (1968). This is given by

$$\beta = \text{Median}\left[\frac{(X_j - X_i)}{j - i}\right] \quad \text{for all } i < j,$$

where X_i and X_j are the sequential data values at times i and j, respectively.

4.1 Considering serial and cross-correlation

While the MK test measures the existence of significant trends at an individual station, the presence of positive serial correlation and cross-correlation could increase the possibility of rejecting a null hypothesis of no significant trends when it may actually be true (von Storch 1995; Lettenmaier et al. 1994; Douglas et al. 2000). This could therefore affect the results of the trend tests, thus reducing the effective number of stations and possibly leading to wrong conclusions being drawn that could have a real negative practical impact, particularly to water management strategies. It is therefore necessary to take into account cross-correlation and serial correlation, the former being carried out by performing a field-significance test (Livezey and Chen 1983; Burn and Hag Elnur 2002; Yue et al. 2002; Yue and Pilon 2003; Yue and Wang 2002).

A modified version of the trend-free pre-whitening (TFPW) procedure proposed by Yue et al. (2002) has been applied in this study to reduce the effect of serial correlation. This method involves estimating a slope of the monotonic trend for any series found to be serially correlated, removing this trend prior to series pre-whitening and finally adding the monotonic trend that has been calculated to the pre-whitened data series. In order to evaluate the field significance of the trend, the permutation procedure discussed extensively in Yue and Pilon (2003) was employed.

4.2 Rainfall indices

Numerous rainfall indices have been defined in several previous studies. Some studies used the length of wet and dry spells to describe changes in the characteristics of rainfall occurrence (e.g. Herath and Ratnayake 2004; Seleshi and Camberlin 2006). Many studies have used total amount of rainfall, frequency of wet days and rainfall intensity as the rainfall indices (e.g. Moron et al. 2007; Gallant et al. 2007; Schmidli and Frei 2005). Indices such as rainfall intensity and frequency of wet days, classified as percentiles (e.g., 25th, 50th, 75th, 90th, and 95th) of daily rainfall values representing light, moderate, heavy and very heavy rainfall have also been used, such as in the study by Martinez et al. (2007).

The indices introduced in this study, as shown in Table 2, were designed to capture changes in a variety of aspects of rainfall distribution. Here a wet day is defined as a day with rainfall of at least 1 mm. The first index, termed TAR, represents the total amount of rainfall, while the second index, FRE, represents the frequency of daily rainfall values, which exceed the threshold value by at least 1 mm. The third index, rainfall intensity (RI), represents mean wet day rainfall and is calculated as TAR divided by FRE. Two indices of extreme rainfall were also employed in this study; XFRE and XI. In calculating these indices, the mean 95th percentile is used as a threshold, instead of using a common threshold for all stations. This is done in order to ensure that extreme values were applicable to all regions, as in previous studies by Haylock and Nicholls (2000), Manton et al. (2001) and Schmidli and Frei (2005). Extreme rainfall in this paper is defined as the daily rainfall amount on wet days exceeding or equal to the 95th percentile. To calculate the 95th percentile, daily amounts were ranked from lowest to highest for each year. Assuming 365 days in a year, the 95th percentile corresponds to the 18th highest value on an annual time scale. This percentile represents long-term conditions and is determined from the base period of 1975–2004. The

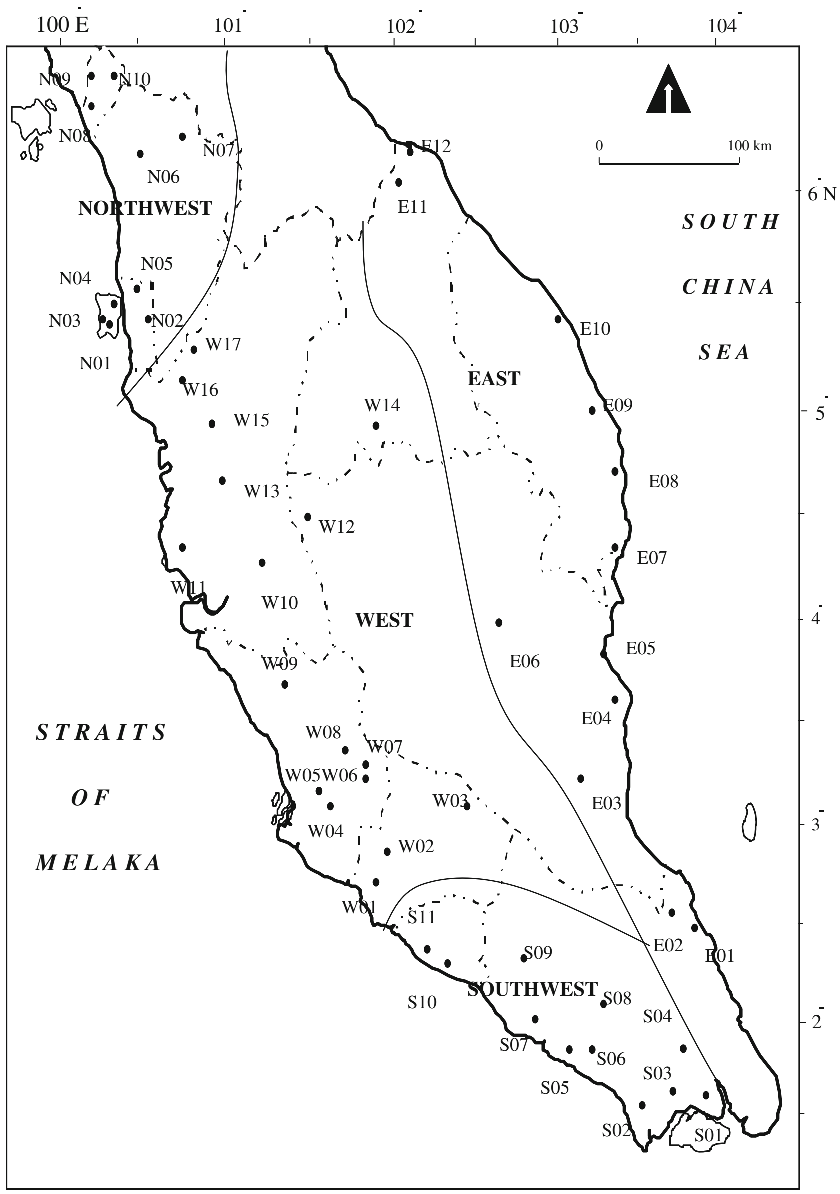

Fig. 2 Map of Peninsular Malaysia showing geographical regions and the selected 50 stations

Table 2 Rainfall indices

Description	Index name
Total amount of rainfall	Total rainfall (TAR)
Frequency of days with at least 1 mm of rain	Frequency (FRE)
Rainfall intensity (mean rainfall on wet days)	Rainfall intensity (RI)
Frequency of daily rainfall exceeding or equal to the 1975–2004 mean 95th percentile (days)	Extreme frequency (XFRE)
Average intensity of events greater than or equal to the mean 95th percentile, i.e. average 18 wettest events (mm)	Extreme intensity (XI)

number of events above the mean long-term 95th percentile is defined as extreme frequency (XFRE), while the average intensity of rain falling in the 95th percentile is known as extreme intensity (XI). All indices were calculated for each year on a seasonal basis.

5 Results and discussion

The following sections discuss the spatial patterns and spatial trends observed in the results based on seasonal rainfall indices.

5.1 Spatial patterns of seasonal rainfall indices

5.1.1 Total rainfall

Figure 3 depicts the spatial distribution of TAR index averages for SWM and NEM season rainfall, recorded during the period 1975–2004. The largest TAR index during the SWM season was seen over the northwestern region, particularly in inland areas with an average value of over 680 mm and a maximum value close to 980 mm. Similar patterns were identified for stations located in the far north of the western region. The large average values observed by these stations may be influenced by their geographical location, in the foothills and sheltered by the mountain range. The greatest amount of rain generally occurs over the foothills and adjacent lowlands, rather than in areas of high altitude (Dale 1959). This explains why a higher amount of rainfall was found in these areas, rather than in other parts of the western Peninsula during the SWM season. Besides those stations, station W04 and the other four nearby stations in the western region also received considerably higher amounts of rain. In contrast, the lowest average amount was found in the lowland areas along the western coast of the Peninsula, areas considered the driest parts of the western Peninsula. In terms of the eastern region, almost all stations record TAR index values of <680 mm and this area can therefore be considered the driest during the SWM season. However, lowland areas located within 20 km of the east coast, close to station E09, are notable as being the wettest parts in the east during the SWM season. Topography and geographical effects may influence the different behavior witnessed at this station as compared to others nearby.

Compared with the SWM season, the range in TAR index values during the NEM season was considerably higher. The largest average TAR index seen during the NEM season was recorded along the eastern coast of the Peninsula, with a value of over 1,100 mm and a maximum value close to 1,900 mm. It is also apparent that the wettest areas in the eastern Peninsula during the NEM season are also the wettest during the SWM season. Apart from these areas, station E02 located in the southern region of the east coast also received the highest average amount of rain. The foothills and lowland areas in the east that face the South China Sea are easily exposed to NEM season flow, resulting in the heavy rainfall observed in these areas. The areas sheltered by the Main Range received a lower average amount of rain than the few areas measured along the western coast of the Peninsula. A large TAR index in the western region is only observed in the area of station W10. This station was also identified as having a large TAR index value during the SWM season. Contrastingly, the lowest average amount of rainfall during the NEM season was observed at all the northwestern stations and in the

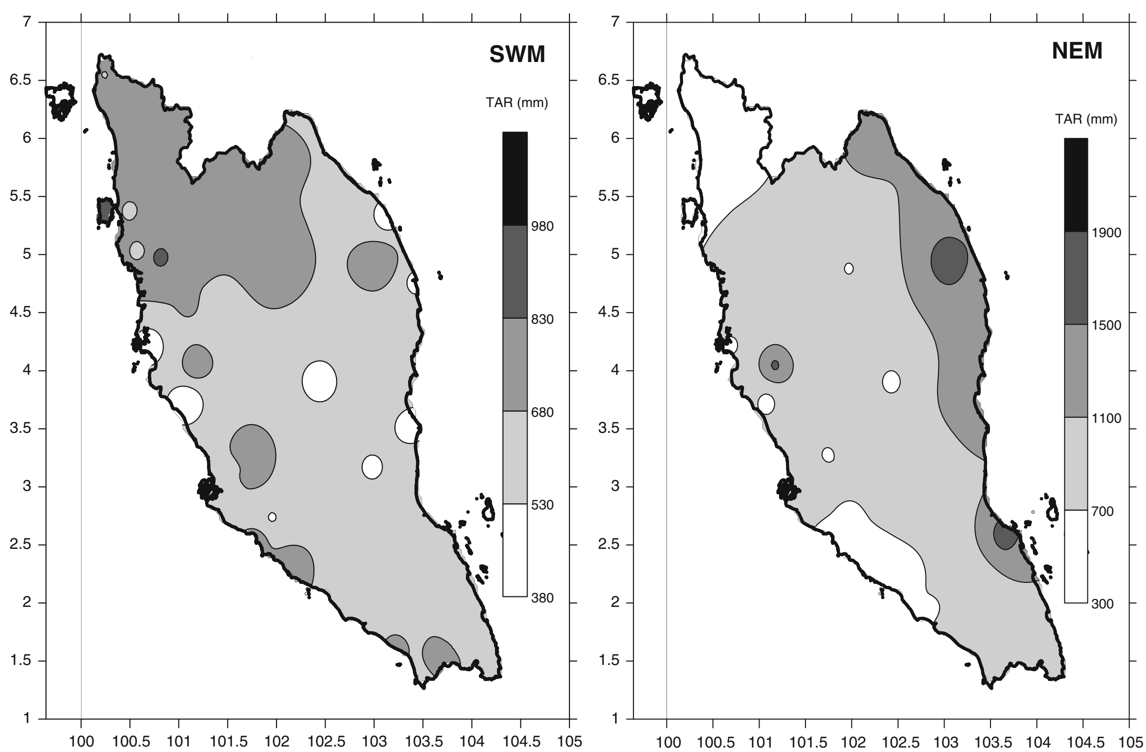

Fig. 3 Spatial distribution of TAR index averages (in mm/year) during the southwest and northeast monsoons

area of stations S10 and S11 in the southwestern region, where <700 mm rainfall was recorded. However, these stations recorded large TAR index values during the SWM season. In general, rainfall patterns for stations in eastern areas are strongly influenced by the NEM season, while there is a lesser impact for stations in the western part of Peninsular Malaysia, especially those in the northwest.

5.1.2 *Frequency of wet days*

Figure 4 depicts the spatial distribution of FRE index averages during the SWM and NEM seasons. An average of more than 41 wet days was observed over the Peninsula during the SWM season, with the largest FRE index identified in several areas including the north of the western Peninsula as well as areas in the northwestern Peninsula. The highland stations in the Main Range such as station W12 experienced the largest FRE index, with an annual average of more than 48 wet days during the SWM season. More wet days were observed in highland than lowland areas in the western part of the Peninsula. It is also noticeable that the area in the eastern region with the largest TAR index also received the largest FRE index. Small parts of the southwestern region, including the area of stations S08, S04, S03, and S01, also received on average more than 48 wet days per year during the SWM season. The lowest FRE index was observed at stations W03 and S02 in the western and the southwestern regions, respectively.

In contrast to the SWM season, larger FRE index values were observed during the NEM season, with most parts of the Peninsula recording an annual average of between 48 and 60 wet days. The highest FRE index value, ranging between 60 and 72 wet days per year, was observed in two areas. The first were the lowland areas located nearly 20 km from the east coast, close to station E09, while the second was the highland station in the Main Range. These two areas were also observed as having the largest FRE index during the SWM season. During the NEM season, the northwestern region recorded the lowest FRE index, with <36 wet days observed. Similar low average values were also observed in the smaller areas of stations W03 and S11.

5.1.3 *Rainfall intensity*

In terms of the RI index, it can be concluded that almost all areas in the Peninsula experienced the same average rainfall intensity of between 10 and 16 mm during the SWM season, as shown in Fig. 5. Only a few places, including stations W03 and W10 stations in the west and stations S02 and S11 in the southwest, recorded more than 28 mm. These four stations recorded the largest RI index during the SWM season. During the NEM season, the largest RI index values were observed in the eastern region, particularly at the stations along the east coast of the Peninsula. A few small and isolated areas near stations W10, W03, and S02, which were found to have the

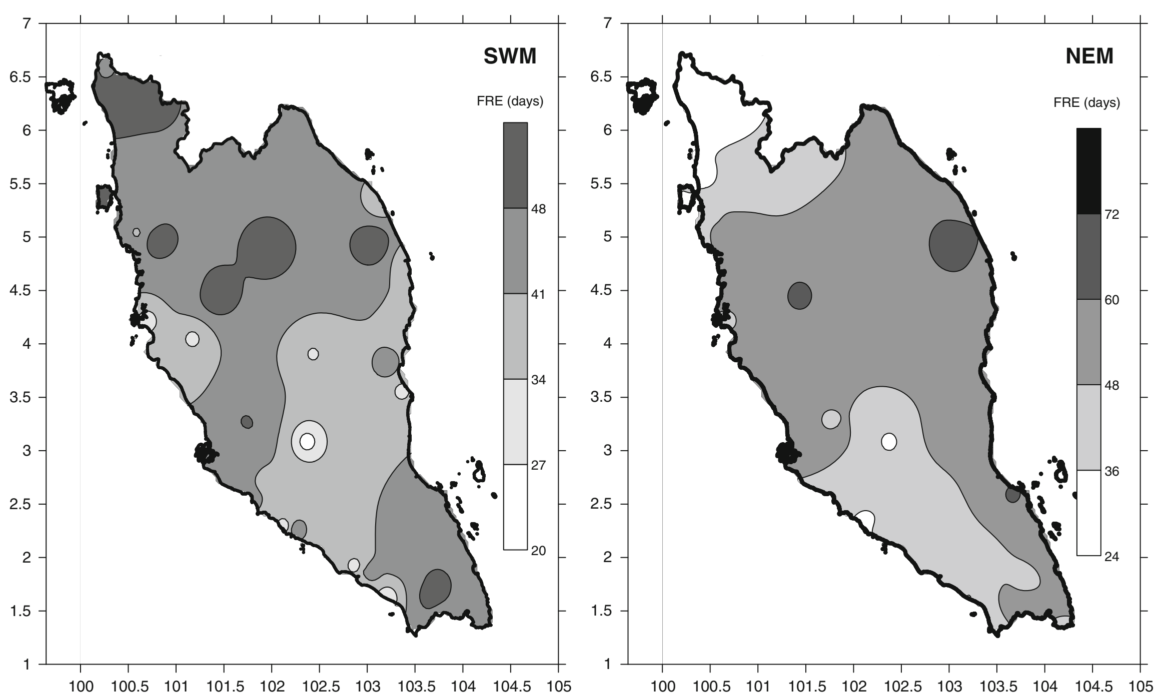

Fig. 4 Spatial distribution of FRE index averages (in days/year) during the southwest and northeast monsoons

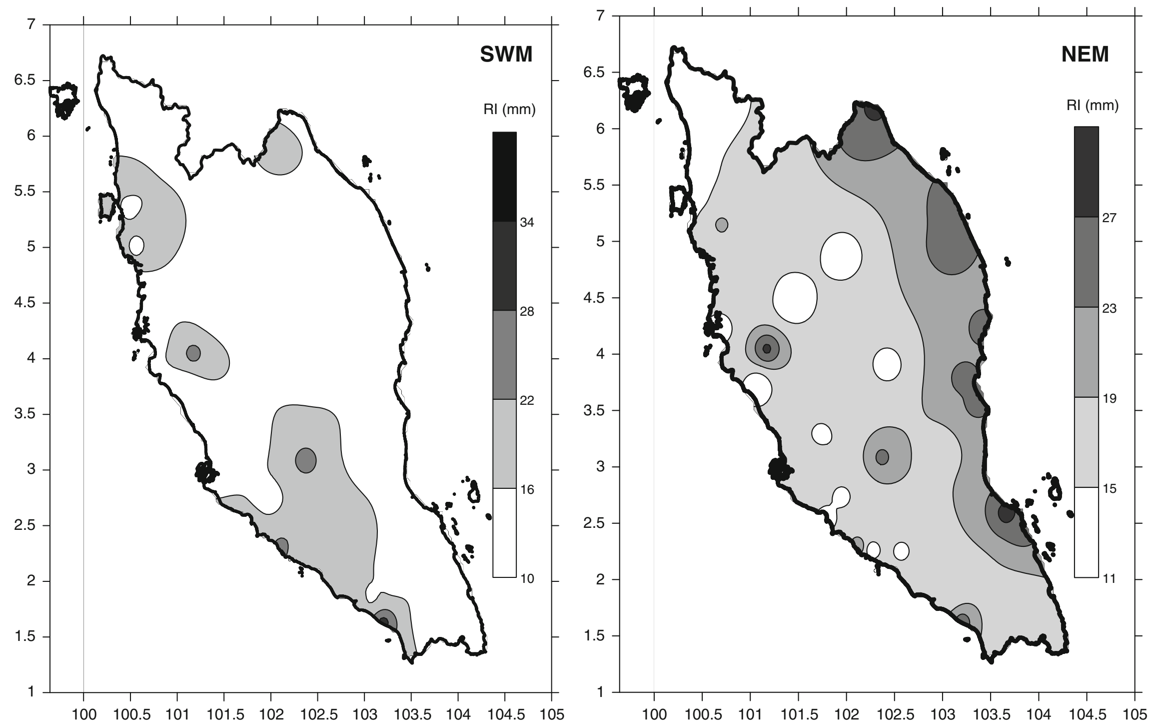

Fig. 5 Spatial distribution of RI index averages (in mm/year) during the southwest and northeast monsoons

largest RI index during the SWM season, also recorded the largest RI index during the NEM season. During this season, the lowest RI index average values of 11 and 15 mm were observed in northwestern areas, highland areas in the Main Range and small areas in the central and western Peninsula.

5.1.4 *Extreme frequency*

The spatial distribution of average XFRE index values during both seasons is displayed in Fig. 6. The largest XFRE index during the SWM season was observed mainly in the western Peninsula, particularly in the area of station W10. In contrast, in the eastern Peninsula, the lowland areas located approximately 20 km from the coast recorded larger XFRE values during this season as compared with other nearby stations in the region. During the SWM season, most areas recorded an average extreme event frequency of between 6.4 and 6.9 wet days. It was also found that the large southwestern Peninsula area recorded the lowest XFRE values during this season. Figure 6 also illustrates that more extreme wet day events were observed in the western part of the Peninsula compared to the eastern area during the NEM season. The lowest XFRE index value was found in the upper north of the eastern Peninsula, with an average of <5.7 wet days. Apart from these areas, a small area in the southwestern region also recorded low XFRE index levels.

5.1.5 *Extreme intensity*

Figure 7 depicts the spatial distribution of XI index averages for both seasons during the studied period. The average values of XI index ranged from 32 to 60 mm during the SWM season, while during the NEM season average values lay between 40 and 160 mm. During the SWM season, the largest XI was observed mainly in the northwestern and western parts of the Peninsula. In contrast, both of these areas experienced the lowest XI during the NEM season, with an average of <60 mm. Here the largest XI was observed at stations along the eastern coast of the Peninsula, with an average value of 140 mm and a maximum close to 160 mm, even though only a small frequency of wet days exceeding the 95th percentile was recorded. These values of XI were much higher than those observed during the SWM season, despite the lower XFRE. These findings suggest that eastern areas are potentially at risk of flooding, landslides, and soil erosion during the NEM season.

5.2 Spatial trends of seasonal rainfall indices

Before applying the non-parametric MK test, the data series of each rainfall index were checked for serial correlation effects. If the series were found to be serially independent, the MK test was then used to assess the significance of any trend. However, if the data series were found to be serially correlated, the TFPW procedure was then applied to correct the data series prior to the non-parametric MK test.

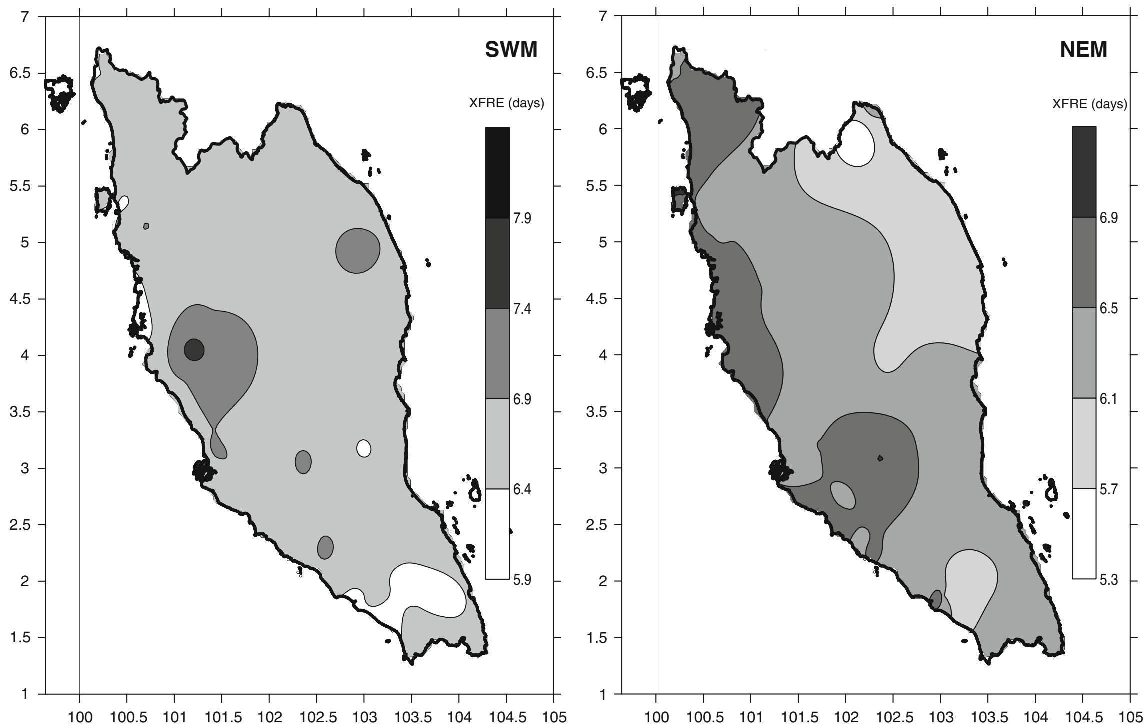

Fig. 6 Spatial distribution of XFRE index averages (in days/year) during the southwest and northeast monsoons

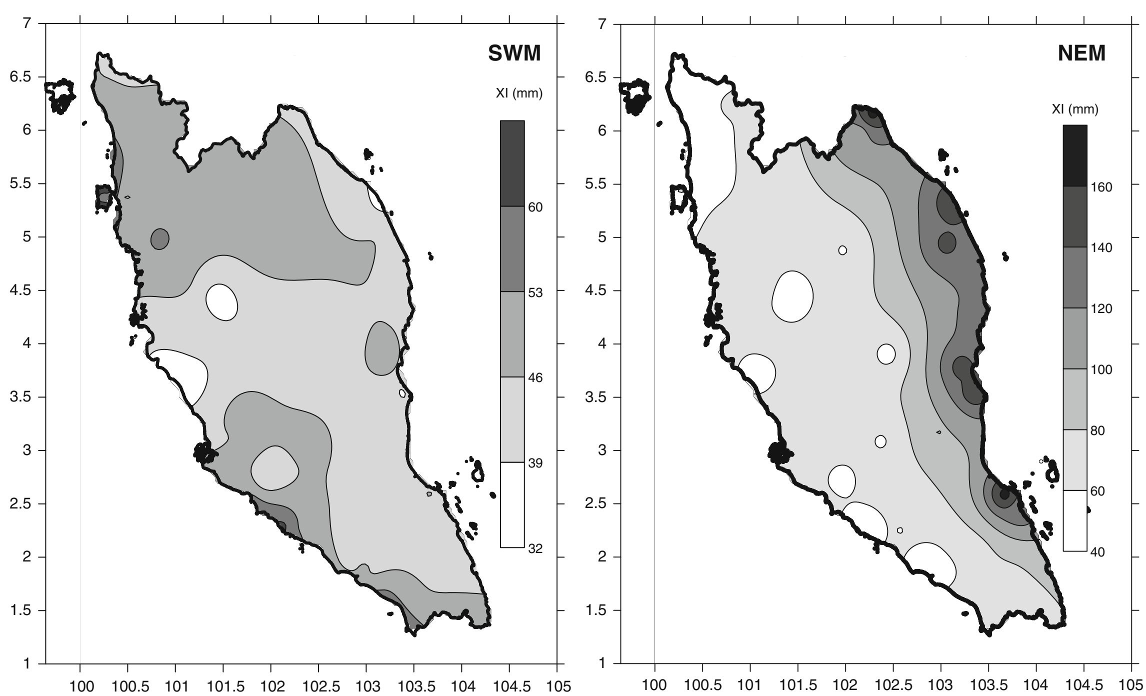

Fig. 7 Spatial distribution of XI index averages (in mm/year) during the southwest and northeast monsoons

Figures 8 and 9 depict the spatial trends of TAR, FRE, RI, XFRE and XI indices for the SWM and NEM seasons. The values of Z statistics from the MK test for individual stations are given in Table 3. The results of magnitude change per unit time of the significant trends detected were computed based on the Theil–Sen estimator and are displayed in Table 4. Further analysis on the field-significant trend was carried out to examine whether trends of rainfall indices at individual stations occurred by chance. Table 5 summarizes the results of the field-significant trend with

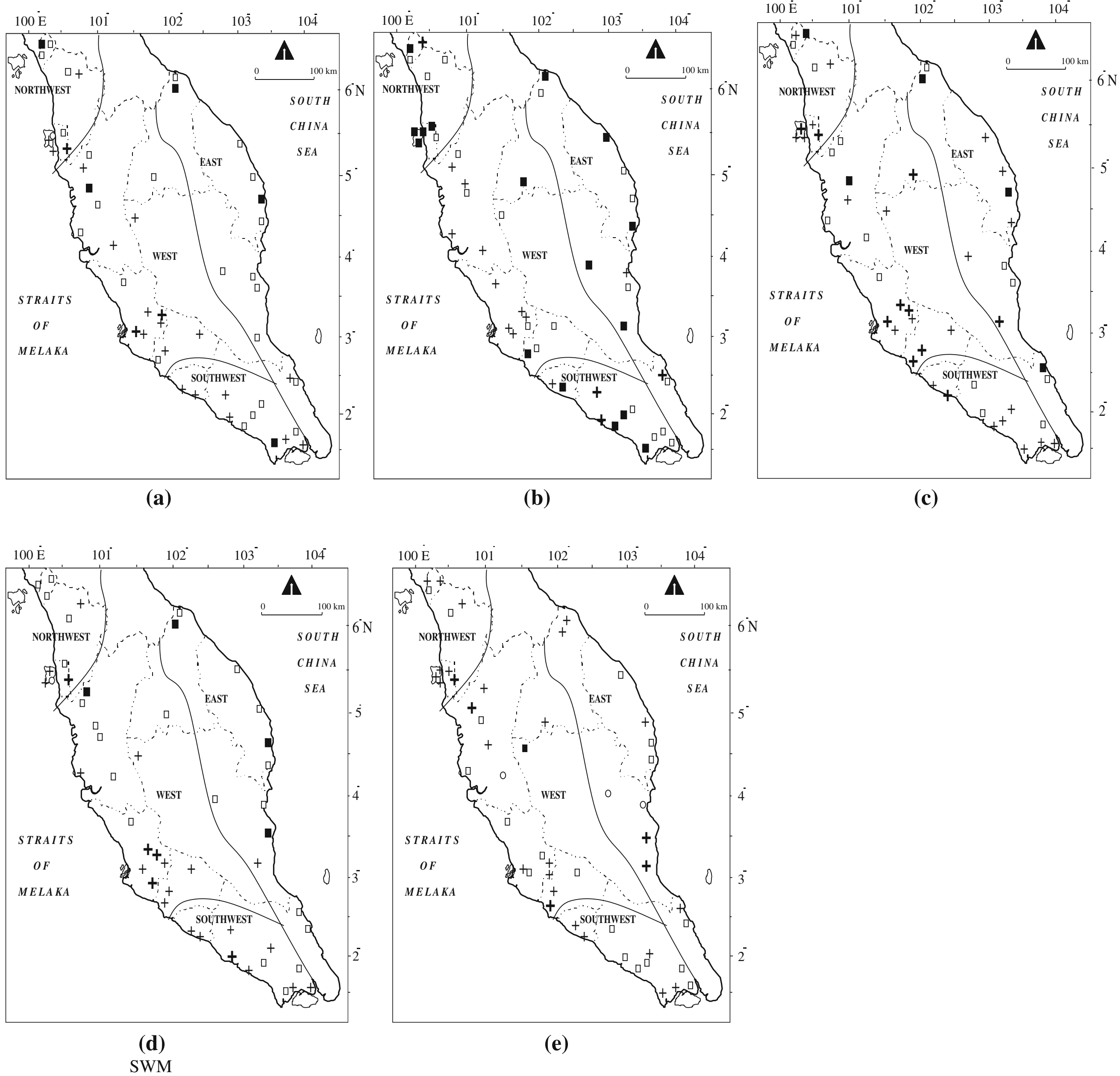

Fig. 8 Spatial trends of southwest monsoon rainfall indices **a** TAR, **b** FRE, **c** RI, **d** XFRE, **e** XI. *Square* negative trend, *plus symbol in bold* significant negative trend, *plus symbol* positive trend, *plus symbol in bold* significant positive trend and *circle* no trend

the number of increasing and decreasing trends for each index at each region over Peninsular Malaysia.

5.2.1 Total rainfall

Figure 8a maps the results of the MK test. Although most stations observed a decreasing trend in TAR index during the SWM season, particularly those in the east, almost all of these were not statistically significant. Only two stations in the eastern area and one station in each of the other three, demonstrated a locally significant decreasing trend during the SWM season. Similarly, while many increasing trends were observed in western area stations, only two were significant. In contrast with the SWM season, the NEM season was characterized by increasing trends in the TAR index for most stations, as shown in Fig. 9a. All stations in the western region exhibited increasing trends, with six of them statistically significant. A similar pattern was observed in the northwest, where almost all stations had increasing trends, three of which were significant. Insignificant increasing trends were observed at most stations in the eastern and southwestern regions, with only one

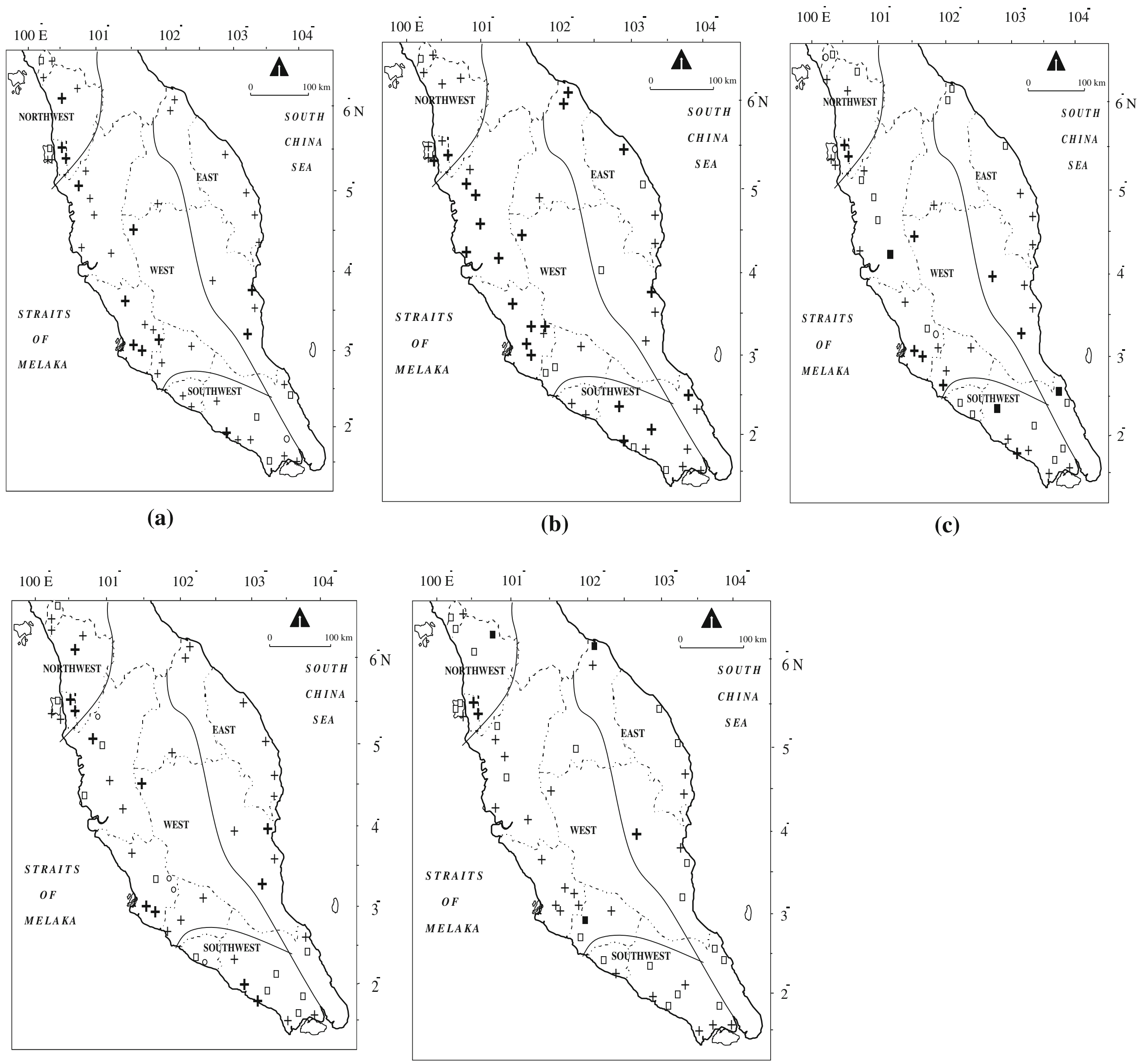

Fig. 9 Spatial trends of northeast monsoon rainfall indices **a** TAR, **b** FRE, **c** RI, **d** XFRE, **e** XI. *Square* negative trend, *plus symbol in bold* significant negative trend, *plus symbol* positive trend, *plus symbol in bold* significant positive trend and *circle* no trend

station in the southwest and two in the east exhibiting significant increasing trends. Based on the results from Table 4, station S02 showed the decreasing trend of largest magnitude, at nearly 12 mm/year during the SWM season. In contrast during the NEM season, no significant decreasing trends were observed at any of the stations, with the largest magnitude of increase, nearly 23.1 mm/year, found at station E05 on the eastern coast of the Peninsula.

It can be observed from Table 5 that no field-significant trend of TAR was found over the Peninsula during the SWM season. On the other hand, in the NEM season, it was found that the northwestern and western areas of the Peninsula showed a field-significant increasing trend in TAR.

5.2.2 *Frequency of wet days*

In terms of FRE index values during the SWM season, very clear decreasing trends for all stations in the eastern, southwestern, and northwestern parts of the Peninsula are depicted in Fig. 8b. Almost all northwestern stations experienced a decreasing trend, five being locally significant. Similarly, several significant decreasing trends were

Table 3 The value of test statistics based on Mann–Kendall test

Region	Station	Southwest monsoon					Northeast monsoon				
		TAR	FRE	RI	XFRE	XI	TAR	FRE	RI	XFRE	XI
Southwest	S01	0.17	−0.84	1.37	1.48	−0.32	0.84	0.84	0.36	1.03	0.99
	S02	**−1.63**	**−1.69**	0.96	−0.75	0.89	−0.54	−1.48	0.58	0.05	1.44
	S03	0.84	−0.11	1.26	0.04	1.48	0.17	1.37	−0.77	−0.53	0.96
	S04	−1.39	−0.88	−0.69	−0.53	−0.73	0.00	0.60	−0.77	−0.17	−0.17
	S05	−0.13	**−1.65**	0.79	0.53	−0.26	1.28	−0.69	**2.53**	**1.69**	−0.62
	S06	−0.43	**−2.10**	1.44	−0.17	−0.92	0.64	0.23	1.18	−1.26	−1.37
	S07	1.52	**2.23**	−1.11	**2.11**	−1.29	**2.38**	**2.06**	0.17	**1.90**	0.71
	S08	−0.13	−1.37	0.84	0.54	0.43	−0.47	**2.01**	−1.59	−1.05	0.58
	S09	0.83	**1.89**	−0.66	1.01	−0.39	1.14	**2.68**	**−1.74**	0.04	−0.34
	S10	0.69	**−1.63**	**2.01**	1.01	0.13	0.84	1.35	−0.62	0.00	0.66
	S11	1.22	1.09	0.51	0.04	0.13	0.96	1.41	−0.99	−0.38	−0.77
East	E01	−0.81	−0.45	−0.39	−0.99	−0.28	−0.13	0.69	−0.54	−0.77	−0.02
	E02	0.13	**3.19**	**−2.72**	−0.71	0.39	0.64	**2.93**	**−1.99**	0.15	−0.36
	E03	−0.17	**−1.89**	**1.97**	0.39	**1.86**	**2.34**	1.13	**1.89**	**1.82**	−1.03
	E04	−0.64	−1.07	−0.24	**−1.93**	**2.19**	1.18	0.90	0.81	1.59	−0.88
	E05	−0.77	0.09	−0.96	−0.77	0.00	**2.42**	**1.99**	1.56	**2.68**	0.43
	E06	−0.96	**−2.46**	1.14	−1.01	0.00	0.84	−0.47	**2.34**	1.01	**1.82**
	E07	−1.41	**−2.04**	0.06	−0.62	−1.37	1.41	0.58	1.29	0.56	0.99
	E08	**−1.93**	−0.84	**−2.16**	**−2.27**	−1.03	0.83	0.38	0.36	0.19	0.21
	E09	−0.39	−1.29	0.62	−0.51	0.43	0.99	−0.36	1.14	1.29	−0.47
	E10	−0.88	**−1.89**	0.73	−0.79	−0.66	0.92	**2.25**	−0.06	0.47	−0.28
	Ell	**−2.93**	−0.56	**−1.82**	**−3.62**	0.08	0.77	**2.03**	−0.47	0.98	0.88
	E12	−1.41	**−2.44**	−0.13	−0.32	0.51	0.24	**2.29**	−0.96	0.49	**−1.97**
West	W01	−0.36	**−3.38**	**3.73**	0.64	**1.67**	1.26	−0.49	**2.42**	1.43	−1.16
	W02	0.09	−0.69	**1.78**	0.43	0.43	0.43	−0.23	0.99	1.18	**−1.82**
	W03	0.23	−0.38	0.62	1.07	−1.21	1.14	1.54	0.81	0.69	0.24
	W04	1.37	1.59	0.66	**1.76**	−0.24	**2.46**	**2.48**	**1.67**	**2.61**	0.26
	W05	**1.78**	0.92	**2.16**	1.48	1.56	**3.25**	**2.95**	**2.64**	**1.89**	0.96
	W06	0.88	−0.15	1.11	0.39	0.30	**1.97**	1.22	1.03	0.00	0.32
	W07	**1.80**	1.05	**1.67**	**1.80**	0.43	1.33	**2.21**	0.02	0.00	0.32
	W08	1.29	0.34	**1.82**	**2.23**	−0.93	0.47	**1.69**	−0.39	−0.51	0.99
	W09	−0.88	0.58	−1.26	−0.53	−1.59	**1.63**	**2.27**	0.84	0.69	0.68
	W10	0.24	0.43	−1.56	−0.79	0.00	0.62	**2.85**	−1.03	0.77	0.79
	W11	−0.28	0.75	−0.92	0.18	−1.11	1.29	**1.69**	0.77	−0.02	0.17
	W12	0.64	−0.11	0.84	1.16	**−2.16**	**2.79**	**2.19**	**1.67**	**2.75**	0.36
	W13	−0.36	−0.39	0.77	−0.06	0.36	1.14	**2.66**	−0.47	1.07	−1.26
	W14	−0.36	**−2.49**	**2.19**	−0.53	1.26	0.77	0.21	1.59	1.20	−0.39
	W15	**−1.63**	0.38	−1.48	−1.40	−1.09	0.51	**2.25**	−0.66	−0.18	0.45
	W16	0.58	1.11	−0.13	−0.09	**1.69**	**2.19**	**3.25**	−0.32	**1.80**	1.56
	W17	−1.11	−0.84	−0.43	**−1.76**	1.28	1.05	1.26	0.13	0.00	−0.23
Northwest	N01	0.06	**−2.19**	0.99	0.00	0.36	1.48	**1.78**	0.96	1.46	0.77
	N02	**2.23**	−1.35	**2.23**	**2.43**	**2.90**	**2.91**	**1.78**	**2.19**	**2.59**	**1.86**
	N03	0.62	**−1.80**	1.44	1.24	0.06	1.11	0.66	0.36	1.52	−0.99
	N04	0.00	**−2.98**	**2.72**	0.53	1.33	−0.21	0.28	0.02	−0.58	−0.39
	N05	−0.43	**−2.51**	1.56	−0.24	1.17	**1.74**	0.58	**2.12**	**1.89**	**1.76**
	N06	−1.14	−1.44	−0.84	−1.33	−0.77	**1.78**	1.26	0.39	**2.03**	−0.17
	N07	0.43	−0.30	0.47	0.19	0.92	0.58	**1.76**	−0.47	0.71	**−1.63**
	N08	−1.41	−0.94	−1.03	−0.73	−0.81	1.11	0.86	0.73	1.24	−0.73
	N09	**−2.03**	**−3.47**	0.28	−1.33	1.33	−0.13	−0.06	0.00	0.62	−0.69
	N10	−0.81	**1.69**	**−2.34**	−1.16	1.44	0.17	1.59	−1.44	−0.02	0.71

The bold face indicates the significant trend at 0.05 level

Table 4 The Theil–Sen's estimator of the slope of significant trends for all rainfall indices at selected station

Station code	TAR	Station code	FRE	Station code	RI	Station code	XFRE	Station code	XI
Southwest monsoon									
S02	−11.89	S02	−0.62	S10	0.14	S07	0.15	E03	0.39
E08	−7.15	S05	−0.26	E02	−0.25	E04	−0.11	E04	0.33
Ell	−8.39	S06	−0.64	E03	0.13	E08	−0.16	W01	0.43
W05	6.91	S07	0.49	E08	−0.15	Ell	−0.17	W12	−0.21
W07	7.75	S09	0.33	Ell	−0.24	W05	0.06	W16	0.26
W15	−6.40	S10	−0.23	W01	0.33	W07	0.14	N02	0.47
N02	6.91	E02	0.89	W02	0.10	W08	0.12		
		E03	−0.31	W05	0.13	W17	−0.13		
		E06	−0.38	W07	0.11	N02	0.13		
		E07	−0.38	W08	0.08				
		E10	−0.37	W14	0.10				
		E12	−0.42	W15	−0.14				
		W01	−0.89	N02	0.27				
		W14	−0.56	N04	0.17				
		N01	−0.33	N10	−0.13				
		N03	−0.26						
		N04	−0.61						
		N05	−0.53						
		N09	−0.57						
		N10	0.21						
Northeast monsoon									
S07	10.80	S07	0.65	S05	0.25	S05	0.15	E06	0.36
E03	13.40	S08	0.37	S09	−0.11	S07	0.13	E12	−1.34
E05	23.07	S09	0.60	E02	−0.34	E03	0.14	W02	−0.36
W04	19.17	E02	0.85	E03	0.17	E05	0.18	N02	0.32
W05	16.21	E05	0.40	E06	0.14	W05	0.18	N05	0.29
W06	11.85	E10	0.44	W01	0.17	W06	0.13	N07	−0.25
W09	7.66	Ell	0.43	W04	0.15	W12	0.16		
W12	11.06	E12	0.40	W05	0.13	W16	0.08		
W16	12.58	W04	0.50	W10	−0.38	N02	0.20		
N02	14.48	W05	0.58	W12	0.10	N05	0.14		
N05	7.42	W07	0.53	N02	0.32	N06	0.16		
N06	5.96	W08	0.30	N05	0.17				
		W09	0.42						
		W10	0.60						
		W11	0.24						
		W12	0.51						
		W13	0.54						
		W15	0.51						
		W16	0.78						
		N01	0.33						
		N02	0.33						
		N07	0.32						

also observed at nearby stations in the southwest, as well as in the eastern region with five stations showing significant decreases in FRE. However, in the western region, only two stations were found to have experienced a significant decline in FRE values. The magnitude of the significant decreasing trends ranged from −0.30 to −0.90 days/year during the SWM season. In contrast, a large number of increasing trends were observed during the NEM season, as

Table 5 The number of stations with non-significant increase, non-significant decrease, significant increase, significant decrease and no trend for each region during the southwest and northeast monsoons

Indices	Region	Southwest monsoon					Northeast monsoon				
		NSI	NSD	SI (*p* value)	SD (*p* value)	NT	NSI	NSD	SI (*p* value)	SD (*p* value)	NT
TAR	Northwest	3	4	1 (0.21)	1 (0.21)	1	5	2	3 **(0.05)**	0	0
	West	8	6	2 (0.13)	1 (0.31)	0	11	0	6 **(0.01)**	0	0
	Southwest	6	4	0	1 (0.21)	0	7	2	1 (0.18)	0	1
	East	1	9	0	2 (0.08)	0	9	1	2 (0.11)	0	0
	Peninsular Malaysia	18	23	3 (0.30)	5 (0.14)	1	32	5	12 **(0.03)**	0	1
FRE	Northwest	0	4	1 (0.19)	5 **(0.01)**	0	7	1	2 (0.08)	0	0
	West	9	6	0	2 (0.14)	0	4	2	11 **(0.00)**	0	0
	Southwest	1	4	2 (0.07)	4 **(0.02)**	0	6	2	3 **(0.05)**	0	0
	East	1	5	1 (0.26)	5 **(0.01)**	0	5	2	5 **(0.01)**	0	0
	Peninsular Malaysia	11	19	4 (0.20)	16 **(0.01)**	0	22	7	21 **(0.01)**	0	0
RI	Northwest	5	2	2 (0.07)	1 (0.09)	0	4	2	2 (0.07)	0	2
	West	5	5	6 **(0.00)**	1 (0.36)	0	7	4	4 **(0.01)**	1 (0.35)	1
	Southwest	7	3	1 (0.26)	0	0	4	5	1 (0.25)	1 (0.35)	0
	East	4	4	1 (0.28)	3 **(0.01)**	0	5	4	2 (0.09)	1 (0.25)	0
	Peninsular Malaysia	21	14	10 **(0.00)**	5 (0.09)	0	20	15	9 **(0.00)**	3 (0.32)	3
XFRE	Northwest	3	5	1 (0.21)	0	1	5	2	3 **(0.05)**	0	0
	West	7	6	3 (0.06)	1 (0.32)	0	7	3	4 **(0.02)**	0	3
	Southwest	7	3	1 (0.22)	0	0	3	5	2 (0.08)	0	1
	East	1	8	0	3 **(0.03)**	0	9	1	2 (0.08)	0	0
	Peninsular Malaysia	18	22	5 (0.10)	4 (0.17)	1	24	11	11 **(0.01)**	0	4
XI	Northwest	7	2	1 (0.21)	0	0	2	5	2 (0.06)	1 (0.22)	0
	West	7	6	2 (0.12)	1 (0.37)	1	12	4	0	1(0.39)	0
	Southwest	5	6	0	0	0	6	5	0	0	0
	East	4	4	2 (0.06)	0	2	4	6	1 (0.28)	1 (0.25)	0
	Peninsular Malaysia	23	18	5 (0.07)	1 (0.18)	3	24	20	3 (0.31)	3 (0.34)	0

The bold cells indicate the *p* value for the region, which has field-significant trends via the permutation test at the significance level of 0.05

shown in Fig. 9b. Locally, significant increases were observed at most stations, particularly in western areas, while no locally significant decreasing trend in FRE was observed at any station during the NEM season. Interesting results were registered by stations E10, E12, and N01, which displayed opposite trends in each season. At all three stations significantly decreasing trends in FRE were reported during the SWM season, while significantly increasing trends were observed in the NEM season. These results indicate that rainfall patterns and trends over Peninsular Malaysia are very much affected by the flow of the two monsoons.

Further analysis of field-significance trends, displayed in Table 5, concluded that the patterns observed in the southwest, northwest, and east represent a field-significant decreasing trend in FRE index during the SWM season. During the NEM season, it is apparent that all regions, except for the northwest, achieved a field-significant increasing trend in FRE index, with the magnitudes of these significant trends ranging from 0.30 to 0.85 days/year. In general, overall FRE index trend results demonstrate that Peninsular Malaysia experienced a field-significant decreasing trend during the SWM season and an increasing trend during the NEM season.

5.2.3 *Rainfall intensity*

The majority of stations indicated increasing RI index trends during the SWM season—except in eastern areas as shown in Fig. 8c. These areas recorded mainly decreasing trends in RI index, with three stations showing statistically significant changes. In contrast, a large number of significant increasing trends in RI index were detected at stations between latitudes of 2.70°N and 3.30°N, in western areas during the same season. Similar patterns for the NEM season were observed, as shown as in Fig. 9c. Four western stations experienced locally significant increasing trends in RI index, while a decreasing trend was observed at five stations—although only one (W10) was large enough to be significant. There was also an increase in RI index during the NEM season for a number of stations in the east and northwest regions, although most of these were not statistically significant. For a few stations, the results indicate that the magnitude of change in RI index is larger during the NEM than the SWM.

In the context of field significance, a field-significant decreasing trend in RI index was seen in eastern areas during the SWM season, a region known to be relatively dry during this period. In contrast, no field-significant decreasing trend in RI index was found during the NEM season. It is also apparent that the overall pattern in the western region was that of a field-significant increasing trend in RI index during both seasons. General findings indicate that the Peninsula as a whole showed a field-significant increasing trend in RI index for both seasons.

5.2.4 *Extreme frequency*

Almost all stations in the eastern region showed a decreasing XFRE index trend during the SWM season, as shown in Fig. 8d. Significant trends were experienced by three stations, with magnitudes ranging from −0.11 to −0.17 days/year. A different pattern was observed in western areas, where a number of increasing trends were found, particularly in at latitudes between 2.70°N and 3.30°N. Trends in XFRE were also observed in northwestern and southwestern regions, but most of these were not significant. In contrast to the SWM season, most areas in Peninsular Malaysia experienced an increasing trend in XFRE during the NEM season, although a decreasing trend was found at a few stations as shown in Fig. 9d. Significant increases were found mainly in western and northeastern areas, with the largest magnitude increasing trend at station N02 of 0.20 days/year. For the NEM season, no significant decreasing trend was detected in any region of the Peninsula.

Based on the results from Table 5, it is apparent that the patterns seen during the SWM season in the eastern region represent a field-significant decreasing trend in XFRE index. However, overall Peninsula SWM results do not show any field-significant trend. Different results were observed during the NEM season, with the northwestern and western regions exhibiting a field-significant increasing trend in XFRE index. Permutation procedure results indicate that overall, in the NEM, the Peninsula experienced a field-significant increasing trend in XFRE index.

5.2.5 *Extreme intensity*

With respect to XI index values, a large number of increasing trends were observed in northwestern areas during the SWM season, as shown in Fig. 8e. The increasing trend of largest magnitude was observed at northwestern station N02 with 0.47 mm in a year, followed by station W01, which experienced an increase of 0.43 mm/year. Overall results indicate that only five stations on the Peninsula showed a significant increasing trend in XI index, while a decreasing trend was observed at only one station during the SWM. Figure 9e shows trends for XI observed during the NEM season. A large number of increasing trends were detected in western areas; however, no significant trend was recorded. Apart from station N02, stations N05 and E06 also exhibited significant increasing XI index trends during the NEM season. In contrast, stations E12, W02, and N07 displayed significantly decreasing trends. The permutation procedure was applied again to determine whether the trends at these stations occurred by chance. It was found that the overall XI index trend pattern in Peninsular Malaysia has no field significance during either monsoon season.

Figures 10 and 11 provide examples of time series for all rainfall indices tested for the NEM and SWM seasons at station N02. N02 is the only station, which was found to experience significant trends, with significant increases detected for all rainfall indices during both seasons, apart from FRE index during the SWM season. The changes in behavior of most rainfall indices at station N02 were detected in 1990 based on graphs displayed in both figures.

6 Conclusion

The results of this study indicate that the highest average for TAR, FRE, RI, XFRE, and XI indices during the SWM season was found in the northwestern region. In contrast, rainfall patterns for eastern stations were mainly characterized by NEM season flow, while a lesser impact was observed in western parts of the Peninsula, especially the northwest. Based on these results, it could be argued that the northwestern stations can more likely be considered the wettest area during the SWM season, since all rainfall indices measured here tend to be higher than those at other stations, particularly those in the east. Conversely, eastern areas could be classified as the driest during the SWM season, although not in the NEM season. The presence of the mountain ranges separating eastern and western parts of the Peninsula could be the best reason to explain the differences in rainfall indices averages received by each region.

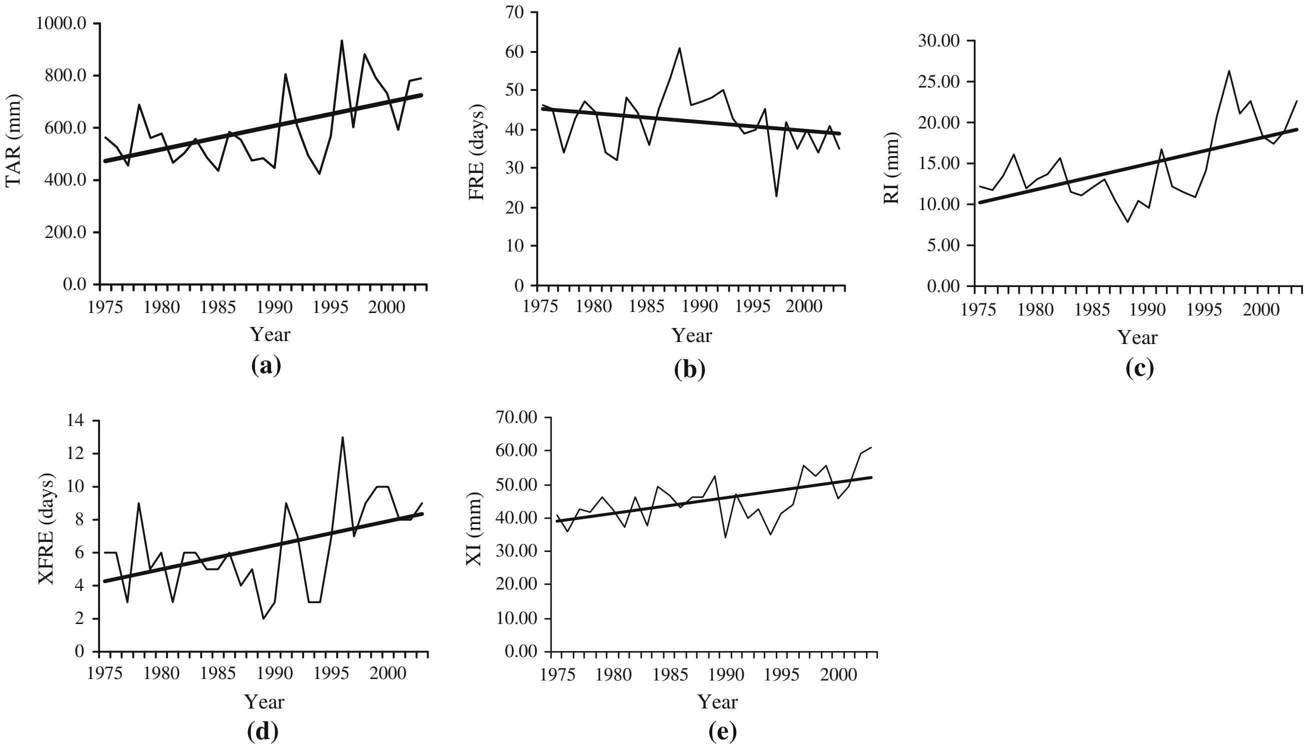

Fig. 10 Time series of rainfall indices **a** TAR, **b** FRE, **c** RI, **d** XFRE, **e** XI at N02 station in the northwestern region during the southwest monsoon

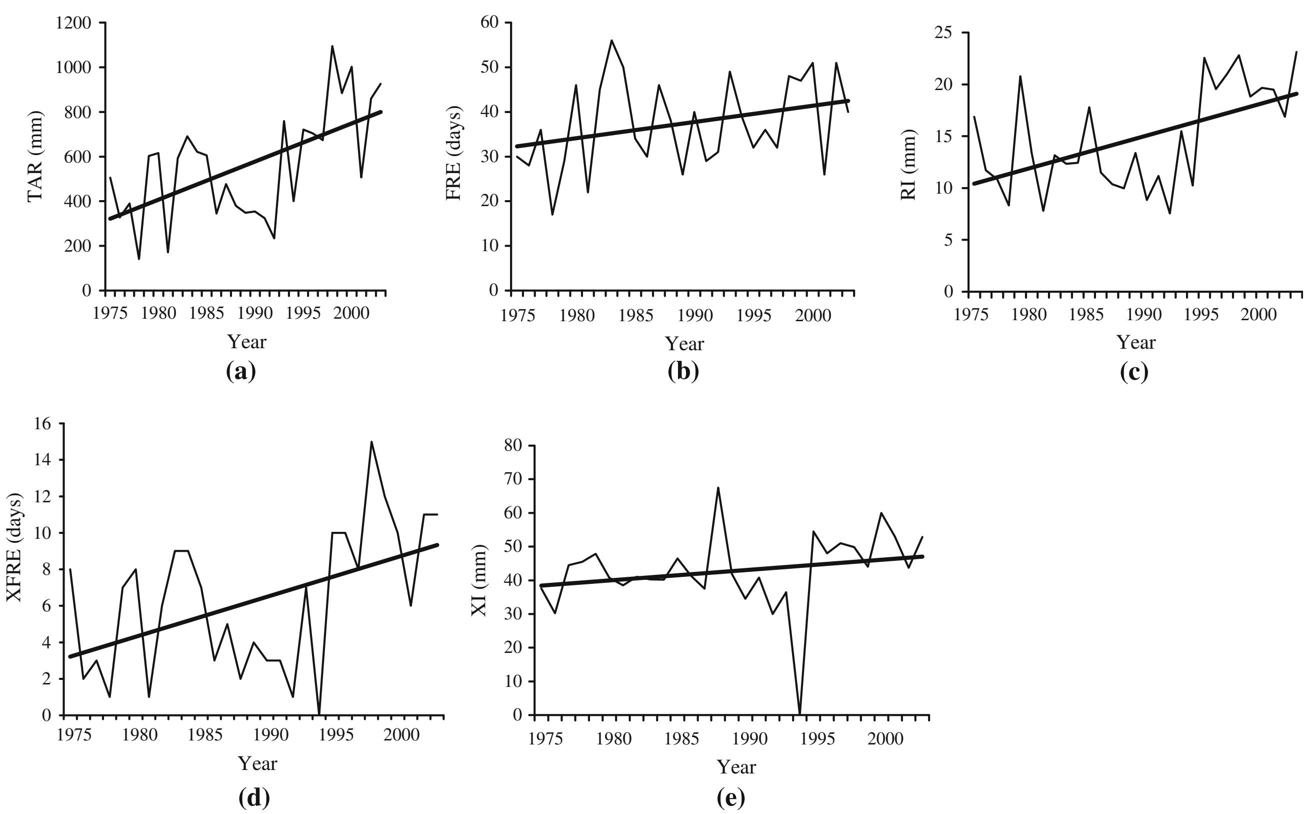

Fig. 11 Time series of rainfall indices **a** TAR, **b** FRE, **c** RI, **d** XFRE, **e** XI at N02 station I the northwestern region during the northeast monsoon

The results of trends during the SWM season indicate that TAR index values decreased insignificantly at most stations, with no field-significant trends attained over the Peninsula. This decrease in TAR index may possibly be associated with the significantly decreasing trends in FRE index. Decreases in TAR and FRE indices also lead to an increase in the RI index, where field-significant increasing trends were observed over most of the Peninsula, apart from eastern areas. During the SWM season, eastern areas can be summarized as experiencing a decreasing trend in TAR index and a significantly decreasing trend in RI index. These patterns are most probably a result of the significant decrease in FRE as well as decreasing frequency of extreme rainfall events. However, general findings over the Peninsula indicate that no field-significant trends in XFRE and XI indices were found for the SWM season. In contrast, results from the Peninsula as a whole during the NEM season showed a field-significant increasing trend in all indices except XI, with no field-significant decreasing trend observed in any index. Significant increases in both TAR and FRE indices were seen, together with a simultaneous increase in RI index. Generally, findings from this study indicate that rainfall patterns over the Peninsula are highly influenced by the NEM season, based on the magnitude of change computed by the Theil–Sen estimator. Larger changes were detected for most stations during the NEM compared with the SWM season.

Potential further studies should investigate changes in the trends of other rainfall characteristics, such as total length of dry and wet spells and the persistency of dry events. More indices related to extreme rainfall events could also be analyzed, with the inclusion of more stations over the Peninsula. Findings derived from these methods should provide more information for the authorities regarding water management strategies as well as predicting future climatic events. In addition, further studies should also take into consideration the relationship between rainfall indices and other climatic variables.

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