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ORIGINAL PAPER

Historical trend of hourly extreme rainfall in Peninsular Malaysia

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Abstract Hourly rainfall data between the years 1975 and 2010 across the Peninsular Malaysia were analyzed for trends in hourly extreme rainfall events. The analyses were conducted on rainfall occurrences during the northeast monsoon (November–February) known as NEM, the southwest monsoon (May–August) known as SWM, and the two inter-monsoon seasons, i.e., March–April (MA) and September–October (SO). Several extreme rainfall indices were calculated at the station level. The extreme rainfall events in Peninsular Malaysia showed an increasing trend between the years 1975 and 2010. The trend analysis was conducted using linear regression; no serial correlation was detected from the Durbin-Watson test. Ordinary kriging was used to determine the spatial patterns of trends in seasonal extremes. The total amount of rainfall received during NEM is higher compared to rainfall received during inter-monsoon seasons. However, intense rainfall is observed during the inter-monsoon season with higher hourly total amount of rainfall. The eastern part of peninsular was most affected by stratiform rains, while convective rain contributes more precipitation to areas in the western part of the peninsular. From the distribution of spatial pattern of trend, the extreme frequency index (Freq >20) gives significant contribution to the positive extreme rainfall trend during the monsoon seasons. Meanwhile, both extreme frequency and extreme intensity (24-Hr Max, Freq >95th, Tot >95th, Tot >99th, and Hr Max) indices give significant contribution to the positive extreme rainfall trend during the inter-monsoon seasons. Most of the significant extreme indices showed the positive sign of trends. However, a negative trend of extreme rainfall was found in the northwest coast due to the existence of Titiwangsa Range. The extreme intensity, extreme frequency, and extreme cumulative indices showed increasing trends during the NEM and MA while extreme intensity and extreme frequency had similar trends during the SWM and SO throughout Peninsular Malaysia. Overall, the hourly extreme rainfall events in Peninsular Malaysia showed an increasing trend between the year 1975 and 2010 with notable increasing trends in short temporal rainfall during inter-monsoon season. The result also proves that convective rain during this period contributes higher intensity rains which can only be captured using short duration rainfall series.

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1 Introduction

Recent increases in the frequency and intensity of extreme rainfall events have raised concern that human activity might have resulted in an alteration of the climate system. It is believed that rise in both frequency and intensity of extreme rainfall events are the major impacts of global warming (Sen Roy 2009; Cheng et al. 2012). Intense rainfall occurrences in short temporal scales or persistent rainfall over long period of time often lead to massive floods resulting in hazardous situations. Peninsular Malaysia experiences unpredictable rainfall events, which causes havoc, and fixing them costs millions of Malaysian ringgit. The increase in massive flood cases, including flash flood and landslides in the last decade, is due to the increase in rainfall intensities.

Several factors such as urban heat island (UHI) effect and local temperature changes contribute to the extreme rainfall events. Large-scale climatic fluctuations, such as the position of the Madden-Jullian oscillation (MJO) and the El-Nino southern oscillation (ENSO) phases, may also modulate the frequency and amount of precipitation on a wet day (Cayan et al. 1999). For instance in Malaysia, the occurrence of the two most extreme ENSOs in 1982/1983 and 1997/1998 were reported to be the factor responsible for extreme climate changes in Peninsular Malaysia (Zin et al. 2010). However, due to local factors too, extreme rainfall events may present contrasting behavior in different regions across Malaysia. A number of studies involving the determination of extreme rainfall trend were done using daily rainfall data with different intensity categories defining extreme rainfall events. For instance, Griffiths et al. (2003) investigated the relationship between the South Pacific Convergence Zone and extreme rainfall trend using indices which considered both extreme frequencies and intensities in the tropical South Pacific. Correlation between indices and the total rain was also determined in this study. Schmidli and Frei (2005) found increasing trends in heavy precipitation during autumn and winter in Switzerland over the period 1901–2000. In other region, Haylock and Nicholls (2000) found decreasing trend in extreme frequency and extreme intensity in southwest Western Australia, while an increasing trend was found in extreme precipitation of eastern Australia.

These findings agree with several studies done throughout the Asian region particularly in Malaysia. Suhaila et al. (2010) found increasing trends in both the total amount of rainfall and the frequency of wet days during the northeast monsoon, which give rise to the increasing trend of rainfall intensity for the period of 1971–2004. Similarly, increasing trends in the extreme intensity indices also were found by Zin et al. (2010) for the period of 1975–2004. However, both studies have found a significant decrease in the number of wet days during this period. Besides extreme rainfall trends, extreme temperature and dry spell trends are also being studied in some regions. Alexander and Arblaster (2009) found increasing trends in temperature extremes, particularly a significant increase in the number of warm nights and heat waves with much longer dry spells interspersed with periods of increased extreme precipitation over Australia. Studies in Peninsular Malaysia found that most of the dry spell indices depicted downward trends during the northeast monsoon over the years of 1975 to 2004.

Analyzing seasonal hourly trend of extreme rainfall events will give a better insight to extreme rainfall behavior compared to daily trends. Haylock and Nicholls (2000) argued that analysis of extreme rainfall, based on total daily rainfall is problematic due to varying quality of the data. In 2009, Sen Roy has proven that hourly data indicated more detailed results, where the trend of maximum hourly rainfall in the eastern part of the Gangetic Plain and Uttaranchal showed an increasing trend during winter, dry-summer, and wet-summer monsoon season, which contrasted an earlier study using daily rainfall showing a decreasing trend of daily extreme rainfall in these same areas (Sen Roy and Balling 2004). Similar studies on daily rainfall data was also conducted in Malaysia by Zin et al. (2010). Increasing trends in several extreme indices were reported. However, analyzing hourly rainfall could give a better indication of the seasonal contribution to the annual extreme rainfall as mentioned earlier. Hence, this study proposes to (1) analyze the trends of extreme hourly rainfall events across Peninsular Malaysia, and (2) describe the profile of hourly extreme rainfall in Peninsular Malaysia. The use of hourly rainfall with a large number of indices and over a long historical period will produce a more accurate account of the spatial distribution and trend of extreme rainfall in Malaysia.

2 Data

Peninsular Malaysia is located between 1° and 6° N in the northern latitude and between 100° to 103° E longitude. The surface climate is influenced by the NEM between November and February and by SWM between May and August. The NEM monsoon is usually associated with heavier rainfall with the eastern and southern regions being the most affected areas. In between these two monsoons are the inter-monsoon seasons occurring in March–April (MA) and September–October (SO), which brings intense convective rainfall to the western coast of Peninsular Malaysia.

In this study, hourly rainfall data were sourced from the Malaysia Drainage and Irrigation Department (DID). The rainfall stations were selected based on two criteria: (1) adequacy of data and length of record and (2) even distribution of rainfall stations across Peninsular Malaysia. Stations with missing values, greater than 2 % of the total record hours within 1 January 1975 to 31 December 2010, were excluded. The average nearest neighbor (ANN) was used in ensuring the stations chosen are spread evenly over the Peninsular Malaysia. The average nearest neighbor ratio is given as follows:

$$ANN = \frac{\overline{D}_0}{\overline{D}_E} \quad (1)$$

where $\overline{D}_0$ is the observed mean distance between each station and their nearest neighbor,

$$\overline{D}_0 = \sum_{i=1}^{n} \frac{d_i}{n} \quad (2)$$

and $\overline{D}_E$ is the expected mean distance for the stations given a random pattern,

$$\overline{D}_E = \frac{0.5}{\sqrt{n/A}} \quad (3)$$

d_i equals the distance between station i and its nearest station, n corresponds to the total number of features, and A is the total study area. The z_{ANN}-score for the statistic is calculated as follows:

$$z_{ANN} = \frac{\overline{D}_0 - \overline{D}_E}{SE} \tag{4}$$

where

$$SE = \frac{0.26136}{\sqrt{n^2/A}} \tag{5}$$

If the z_{ANN}-score is less than 1, the stations are clustered. Otherwise, the stations are spread evenly. The calculated z_{ANN}-score is 2, which falls into a category of dispersed distribution at 99 % level of significance. Using these criteria, 25 stations (Table 1) were selected for this study. The distribution of stations is portrayed in Fig. 1.

3 Methodology

In this study, 8 seasonal extreme rainfall indices were examined based on hourly rainfall data at the 25 selected stations. The extreme rainfall indices, chosen after Sen Roy (2009) considered both the intensity and frequency of extreme rainfall events (Table 2). A rainfall amount of at least 0.1 mm is chosen as a threshold for hourly rainfall. In this study, percentiles were used rather than fixed threshold as it is a more accurate measure and suitable for a region like Peninsular Malaysia which has highly variable rainfall and high spatial rainfall intensity (Haylock and Nicholls 2000; Griffiths et al. 2003). The 95th and 99th percentile was selected as the threshold to represent extreme rainfall events. All precipitation events above 0.1 mm occurring throughout the entire study period were sorted in ascending order for each station separately, in order to determine the threshold value for the 95th and 99th percentile. Next, the total amount and frequency of events occurring each year above the 95th and 99th percentile were calculated. Hours with rainfall exceeding 95th percentile were referred to as very wet and hours with rainfall exceeding 99th percentile as extremely wet.

Table 1 Name of stations with longitude and latitude

No.	Station	Name of station	Long (°)	Lat (°)
1	1737001	Sek. Men. Bukit Besar, Kota Tinggi Johor	103.72	1.76
2	2224038	Chin Chin (Tepi Jalan) Melaka	102.49	2.28
3	2719001	Setor JPS Sikamat Seremban	101.54	2.73
4	2815001	Pejabat JPS Sungai Mangga Selangor	101.54	2.82
5	2818110	SMK Bandar Tasik Kesuma, Semenyih Selangor	101.87	2.89
6	2913001	Pusat Kawalan P/S Telok Gong Selangor	101.39	2.93
7	3117070	JPS Ampang, Selangor	101.75	3.15
8	3118102	Sek. Keb. Kg. Lui Selangor	101.87	3.17
9	3314001	Rumah Pam JPS Jaya Setia Selangor	101.41	3.36
10	3411017	Stor JPS, Tg Karang Selangor	101.17	3.42
11	3516022	Loji Air Kuala Kubu Bharu Selangor	101.45	3.57
12	3613004	Ibu Bekalan Sg. Bernam Selangor	101.35	3.69
13	3710006	Rumah Pam JPS Bangunan Terap, Selangor	101.08	3.72
14	4908018	Pusat Kesihatan Kecil, Batu Kurau Perak	100.80	4.97
15	2831179	Kg. Kedaik, Pahang	103.18	2.88
16	3533102	Rumah Pam Pahang Tua, Pekan	103.35	3.56
17	3924072	Rumah Pam Paya Kangsar, Pahang	102.43	3.90
18	4234109	JPS Kemaman, Terengganu	103.42	4.23
19	4734079	Sek. Men. Sultan Omar Dungun, Terengganu	103.41	4.76
20	4819027	Gua Musang, Kelantan	101.99	4.87
21	4930038	Kg. Menerong, Terengganu	103.06	4.94
22	5331048	Setor JPS, Kuala Terengganu	103.13	5.31
23	5504035	Lahar Ikan Mati Kepala Batas, Penang	100.43	5.53
24	6207032	Ampang Pedu, Kedah	100.77	6.24
25	6401002	Padang Katong, Kangar	100.18	6.44

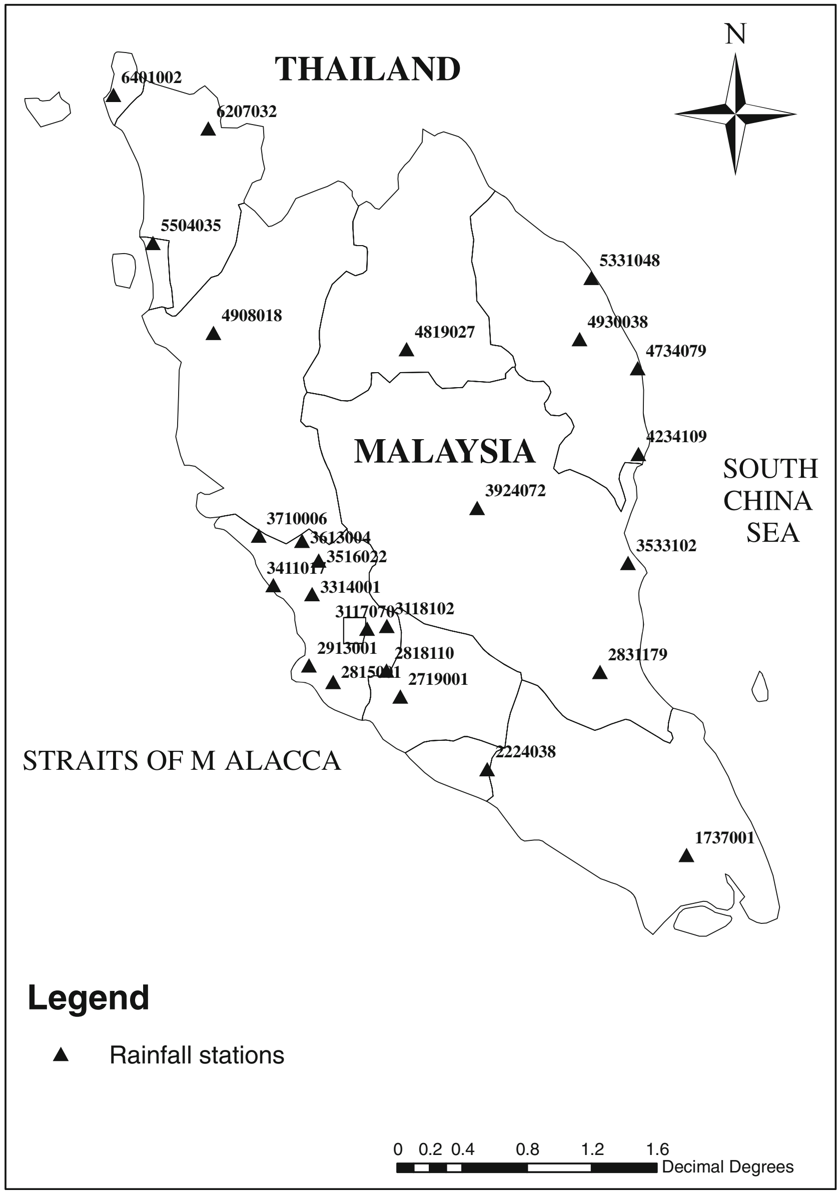

Fig. 1 Distribution of stations used in this study

The trends for each of these 32 indices (8 extreme rainfall indices for 4 seasons) were calculated using least square linear regression analysis method at each station level. For each station, a matrix of 36 rows, 1 for each year from 1975 to 2010, and 9 columns representing the year and each of the 8 variables was developed. Simple linear regression (LS) analysis with the year of record serving as independent variable was established to obtain the standardized regression coefficient, representing the strength and sign of any trend, for each of the eight variables. The significance of this linear fit was tested using t test at 5 % level of significance. Another test to detect the trend within the time series is the nonparametric Mann-Kendall (MK) test. The Mann-Kendall test is based on the statistic S. Each pair of observed values y_i, y_j ($i>j$) of the random variable is inspected to find out whether $y_i>y_j$ or $y_i<y_j$. P is the number of the former type of pairs, and M is the number of the latter type of pairs. Then S is defined as follows:

$$S = P - M \tag{6}$$

For $n>10$, the sampling distribution of S is as follows. Z follows the standard normal distribution where

$$Z = \begin{cases} (S-1)\Big/\sqrt{\mathrm{Var}(S)} & \text{if } S > 0, \\ 0 & \text{if } S = 0, \\ (S+1)\Big/\sqrt{\mathrm{Var}(S)} & \text{if } S < 0 \end{cases} \tag{7}$$

Table 2 Rainfall indices with definitions and units

Definitions	Index name	Unit
Extreme cumulative rainfall		
1. Largest seasonal total amount of rainfall recorded over 24 consecutive hours for each year (24)	24-Hr Max	mm/24-h
Extreme intensity		
2. Annual seasonal hourly maximum amount of rainfall—the seasonal hourly maximum amounts of rainfall were determined separately for each year.	Hr Max	mm/hr
3. Largest seasonal total amount of rainfall recorded over five consecutive hours for each year	5-Hr Max	mm/5-h
4. Total amount of rainfall exceeding 95th percentile for each year	Tot>99th	mm/hr
5. Total amount of rainfall exceeding 99th percentile for each year	Tot>95th	mm/hr
Extreme frequency		
6. Frequency of seasonal rainfall events greater than 20 mm within 1 h for each year	Freq>20	hr
7. Frequency of rainfall exceeding 95th percentile within 1 h for each year	Freq>95th	hr
8. Frequency of rainfall exceeding 99th percentile within 1 h for each year	Freq>99th	hr

There is a correction for ties when $y_i=y_j$. The null hypothesis of no trend is rejected when the computed Z value is greater than z_α in absolute value. These were done separately according to four different seasons of Peninsular Malaysia. After that, the field significance test for each extreme index is tested using the regional average Mann-Kendall test (RAMK) as suggested by Yue et al. (2002). No correlation exist in the rainfall data, hence the regional MK test without spatial and temporal correlation was used in the study. The sum of MK statistics of m independent sites is given by $S_{\mathrm{SUM}}=\sum_{k=1}^{m} S_k$. The standardized RAMK statistic $\overline{S}$ is

$$\overline{Z}=\begin{cases}\left(\overline{S}-1\right)/\sqrt{\mathrm{Var}\left(\overline{S}\right)} & \text{if } \overline{S}>0,\\ 0 & \text{if } \overline{S}=0,\\ \left(\overline{S}+1\right)/\sqrt{\mathrm{Var}\left(\overline{S}\right)} & \text{if } \overline{S}<0\end{cases} \tag{8}$$

where $\overline{S}=S_{\mathrm{SUM}}/m$ is normally distributed and can be represented by $S\sim N\left(\frac{1}{m}\sum_{k=1}^{m}\mu_k,\sum_{k=1}^{m}\sigma_k^2\right)$. The sample mean and variance of the RAMK statistic are $E\left[\overline{S}\right]=0$ and $\mathrm{Var}\left(\overline{S}\right)=\frac{1}{m^2}\sum_{\mathrm{k}=1}^{\mathrm{m}}\mathrm{Var}(S_k)$. Next, ordinary kriging method was employed to determine the spatial patterns of trends in seasonal extremes. Furthermore, the autocorrelation in the rainfall data was also tested using the Durbin-Watson (DW) test where $H_0:\rho=0$ vs. $\mathrm{H}_1:\rho>0$. The test statistic is $d=\frac{\sum_{i=2}^{n}(e_i-e_{i-1})^2}{\sum_{i=1}^{n}e_i^2}$ where $e_i=y_i-\widehat{y}_i$ and y_i and $\widehat{y}_i$ are the observed and predicted values of the response variable for individual i. The DW-statistic for the data was found to be approximately 2, which indicates that there is no autocorrelation in the rainfall data at the 5 % level of significance.

4 Results and discussion

This section will discuss the spatial profile of extreme rainfall indices as well as the spatial trends of seasonal extreme rainfall indices for the whole of Peninsular Malaysia.

4.1 Spatial profile of extreme rainfall indices

As for the extreme intensity and extreme cumulative indices, it is interesting to note that the spatial pattern of rainfall activities over the inter-monsoon season, notably MA, shows a consistent pattern of higher indices in the western region (Figs. 2, 3, 4, 5, and 6). The Hr-Max recorded a higher value in this season compared to other seasons with amount of rainfall reaching up to 49.93 mm. This is in agreement to the general assumption that convective rain occurring during the inter-monsoon period has higher intensities compared to stratiform rain which occur during the monsoon season since the maximum rainfall depicts higher value in a relatively short time (i.e., hourly) and such results cannot be captured using daily data as portrayed by the results of Zin et al. (2010), in which the highest extreme intensities occurred during NEM season. The spatial pattern of the 5 Hr-Max and 24 Hr-Max follows the same pattern. However, the Hr-Max presents a different pattern with higher hourly maximums in the western region indicating that the NEM brings stratiform rain which are long duration heavy rains. The western regions are affected by the NEM but to a lesser degree. Hence immense floods usually occur in the eastern regions during the NEM. The northern part of the peninsular receives little rain during the NEM due to the existence of Titiwangsa Range (Banjaran Titiwangsa) which blocks the region from receiving the rain brought on the

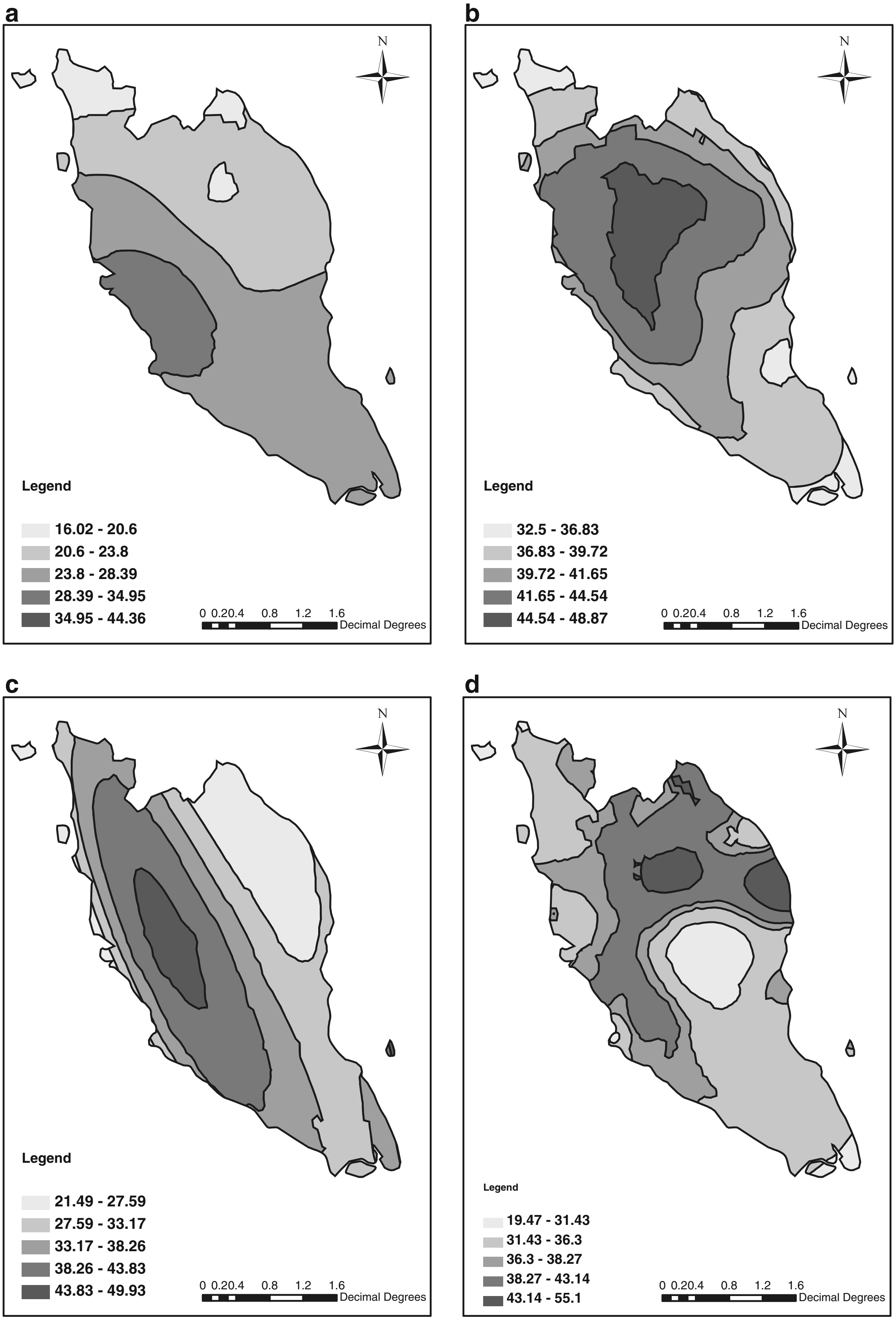

Fig. 2 Spatial distribution of Hr Max index for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

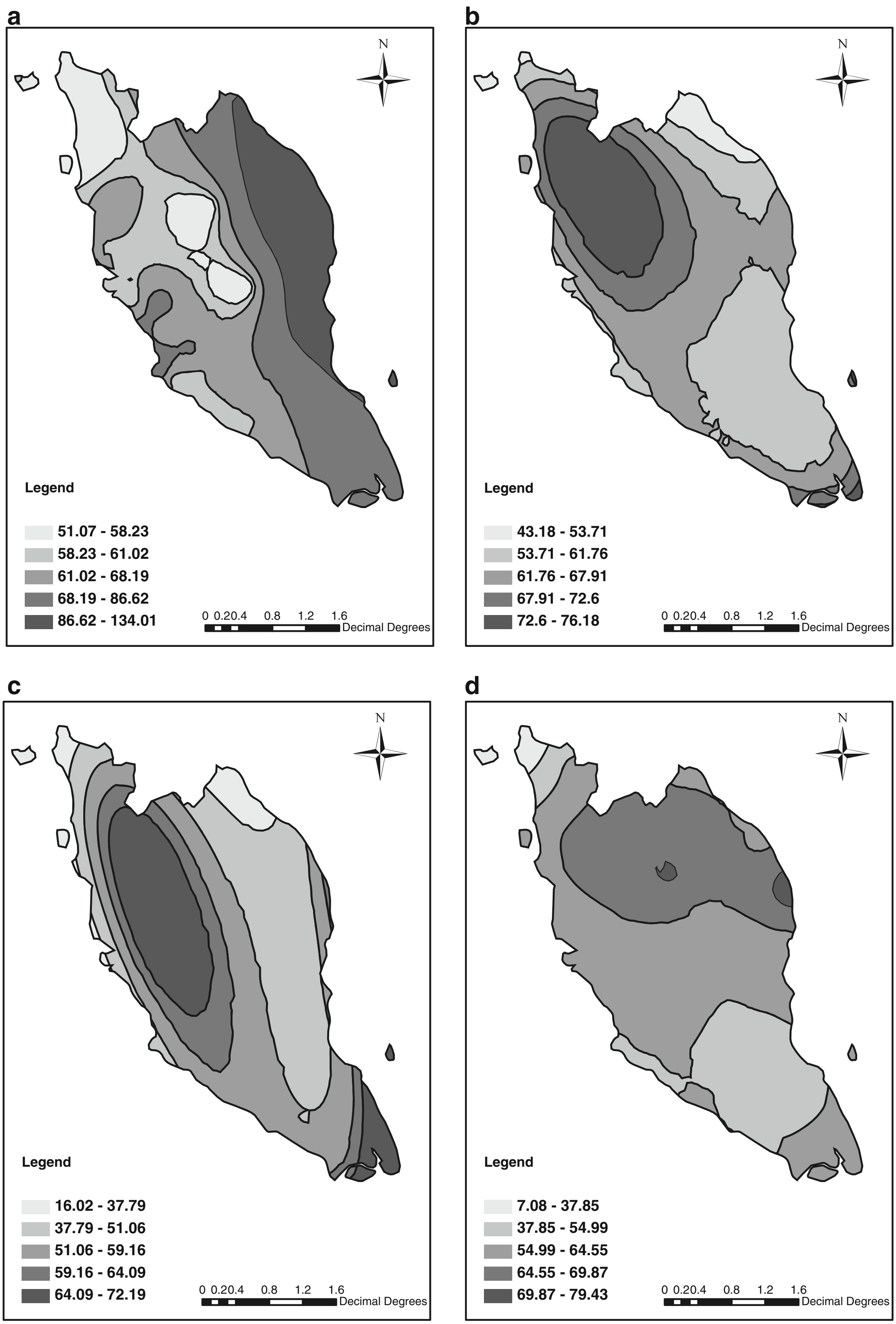

Fig. 3 Spatial distribution of 5-Hr Max index for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

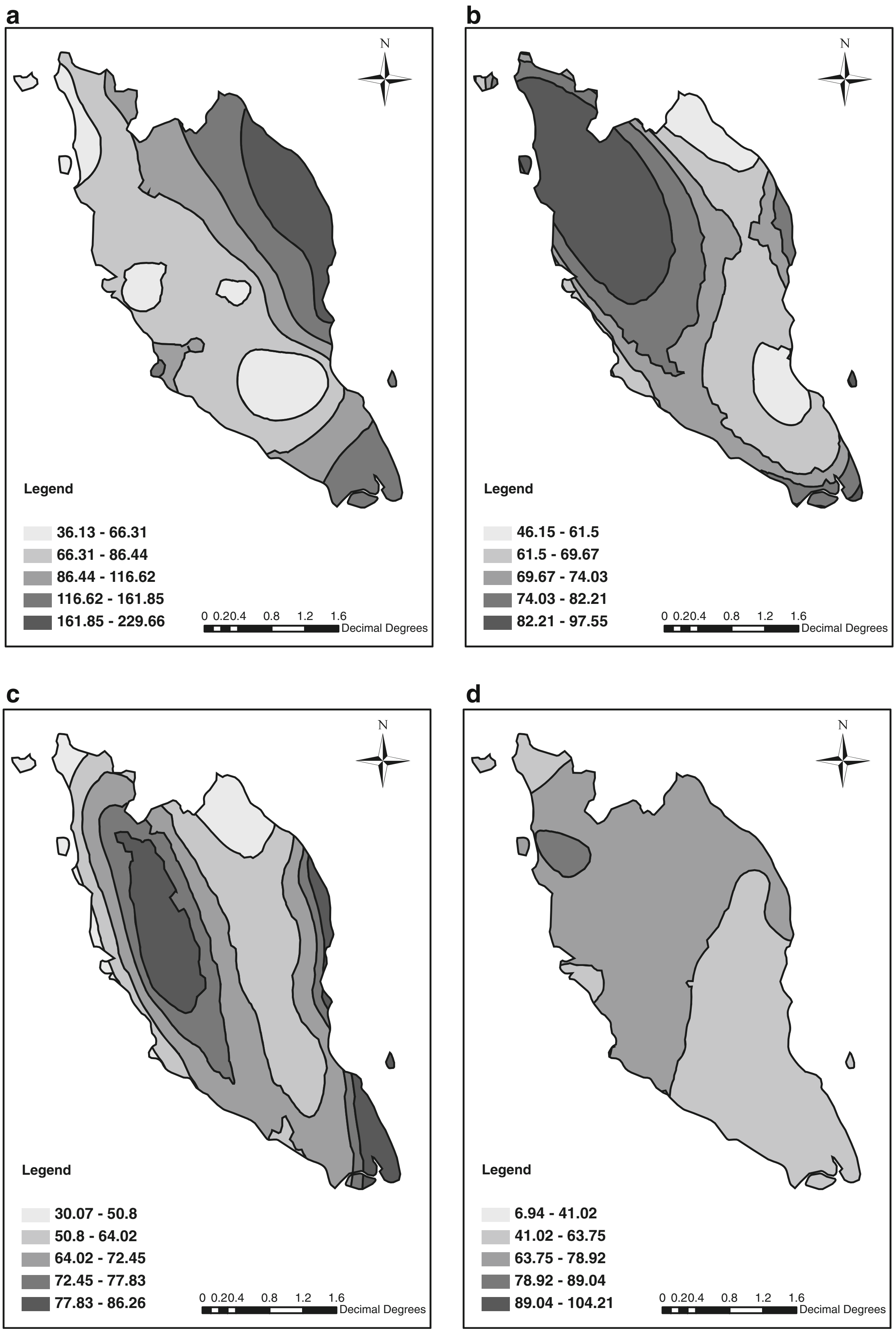

Fig. 4 Spatial distribution of 24-Hr Max index for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

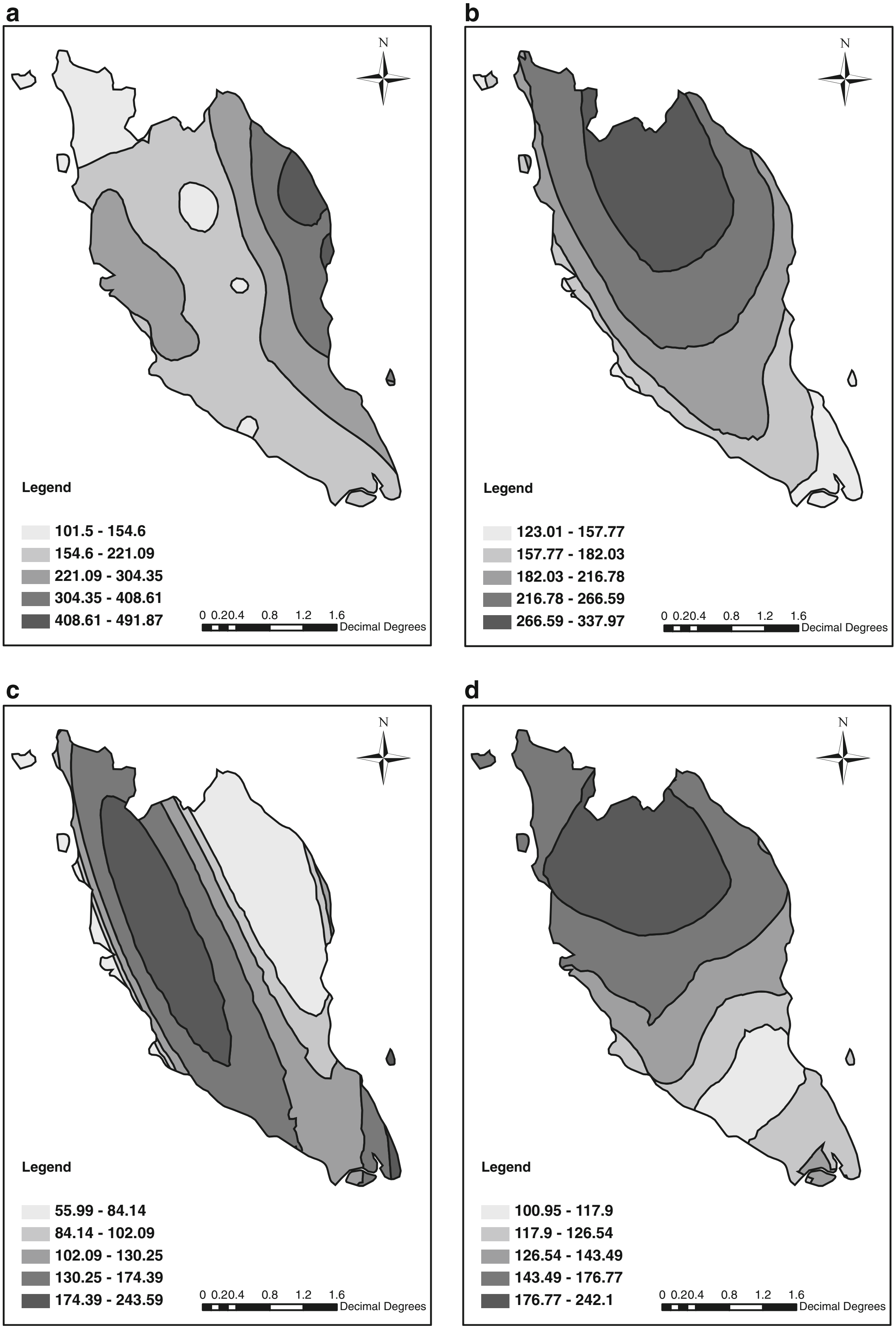

Fig. 5 Spatial distribution of total amount for Tot >95th index, for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

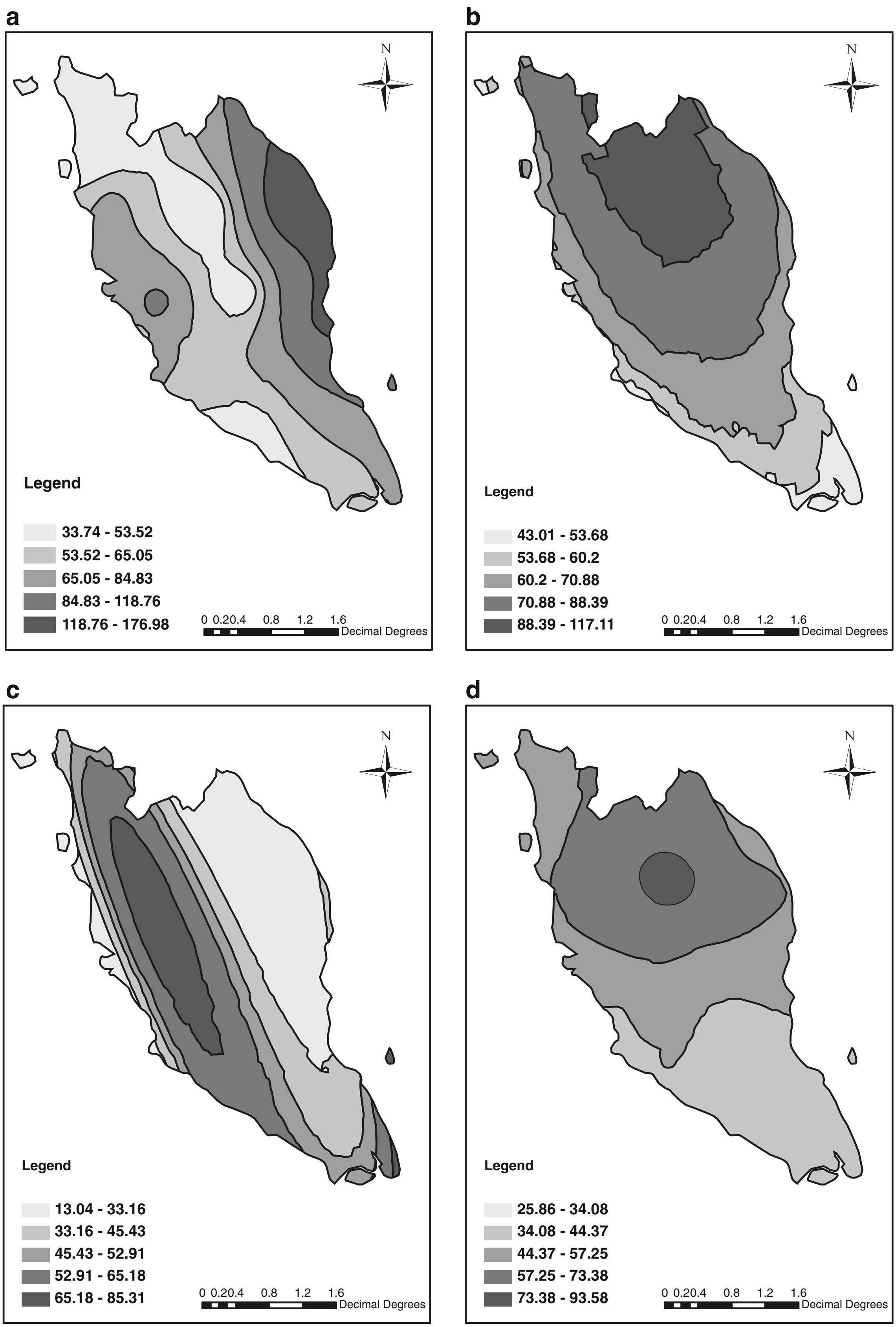

Fig. 6 Spatial distribution of total amount for Tot >99th index for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

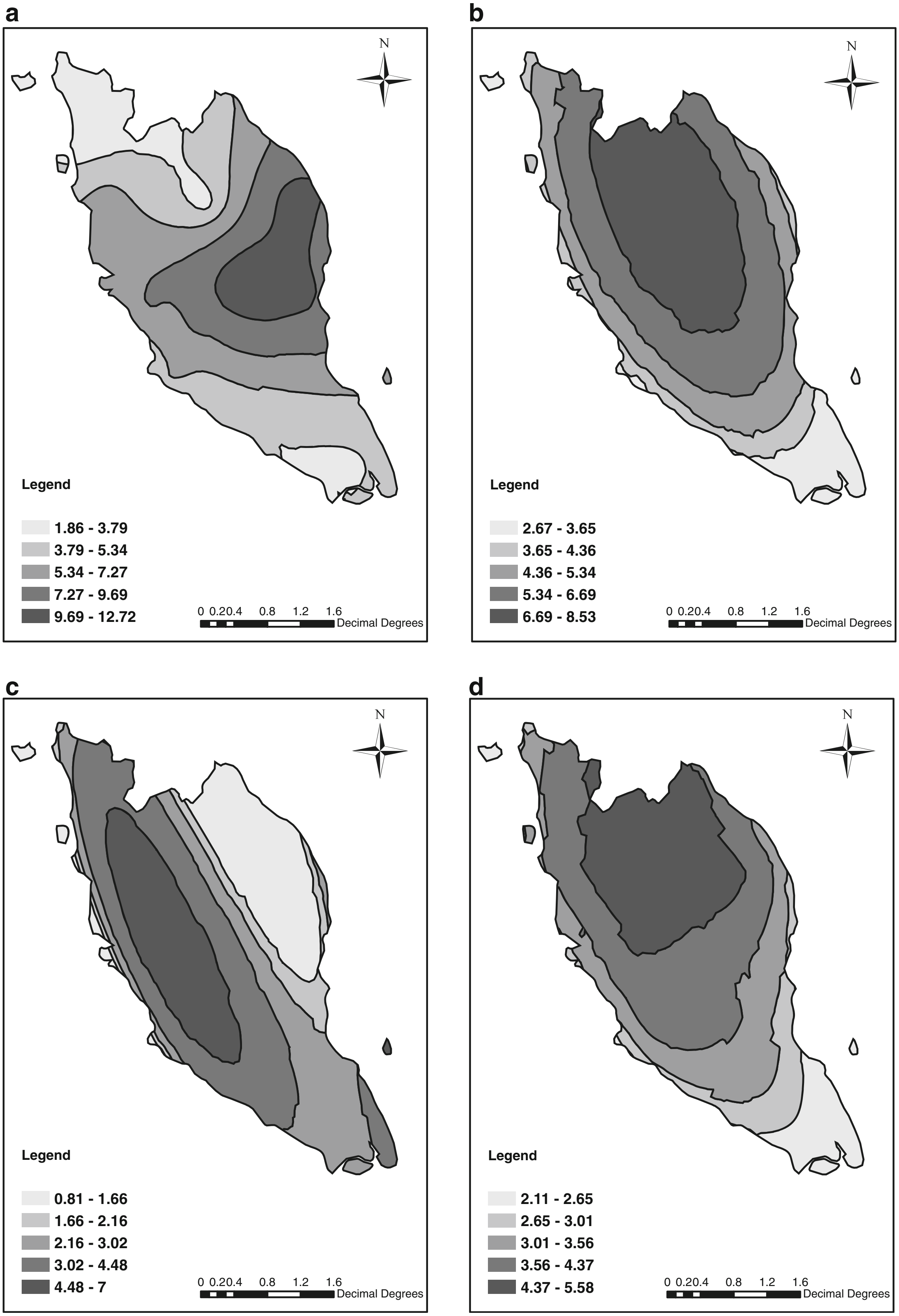

Fig. 7 Spatial distribution of Freq >20 index for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

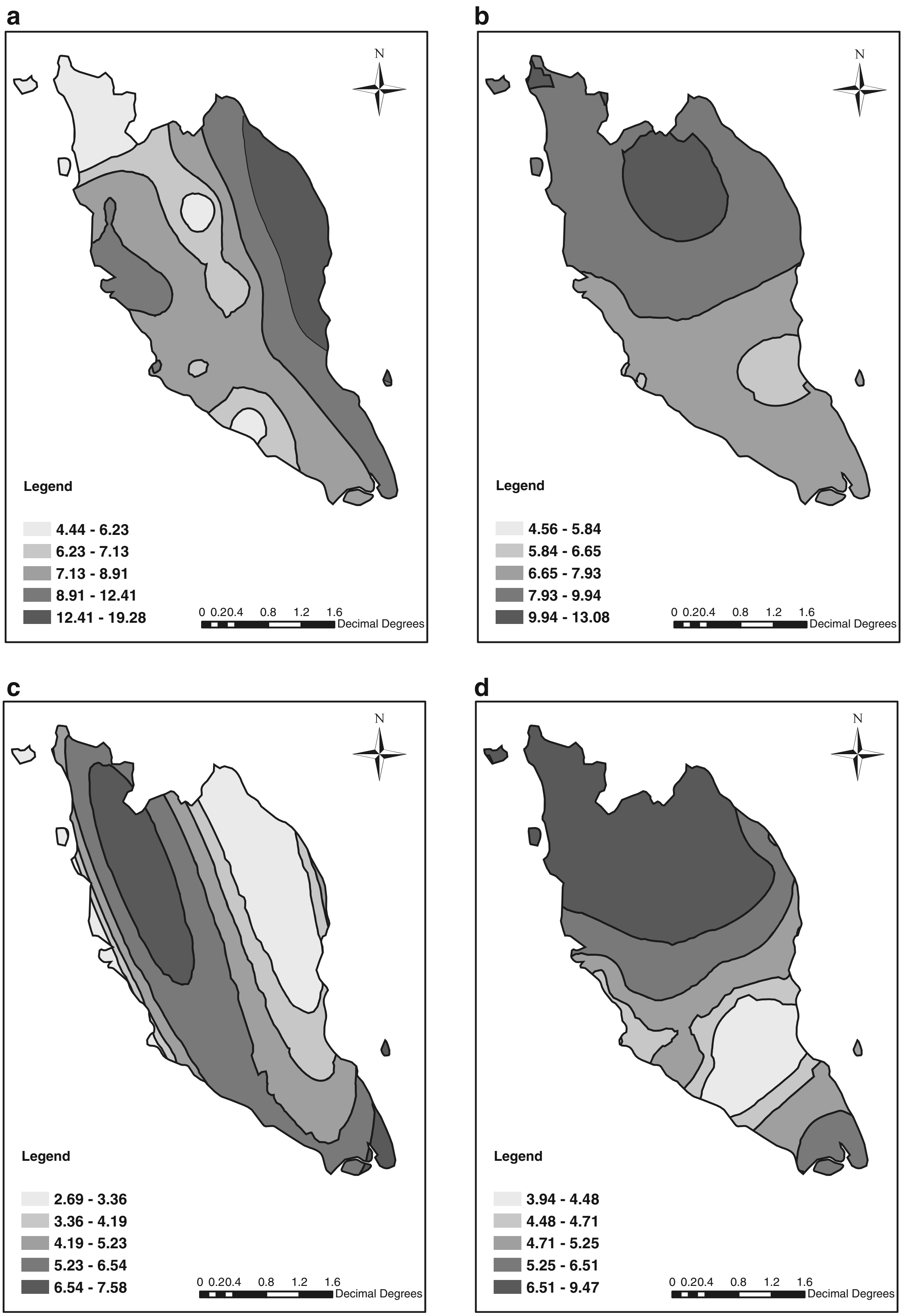

Fig. 8 Spatial distribution of total amount for Freq >95th index for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

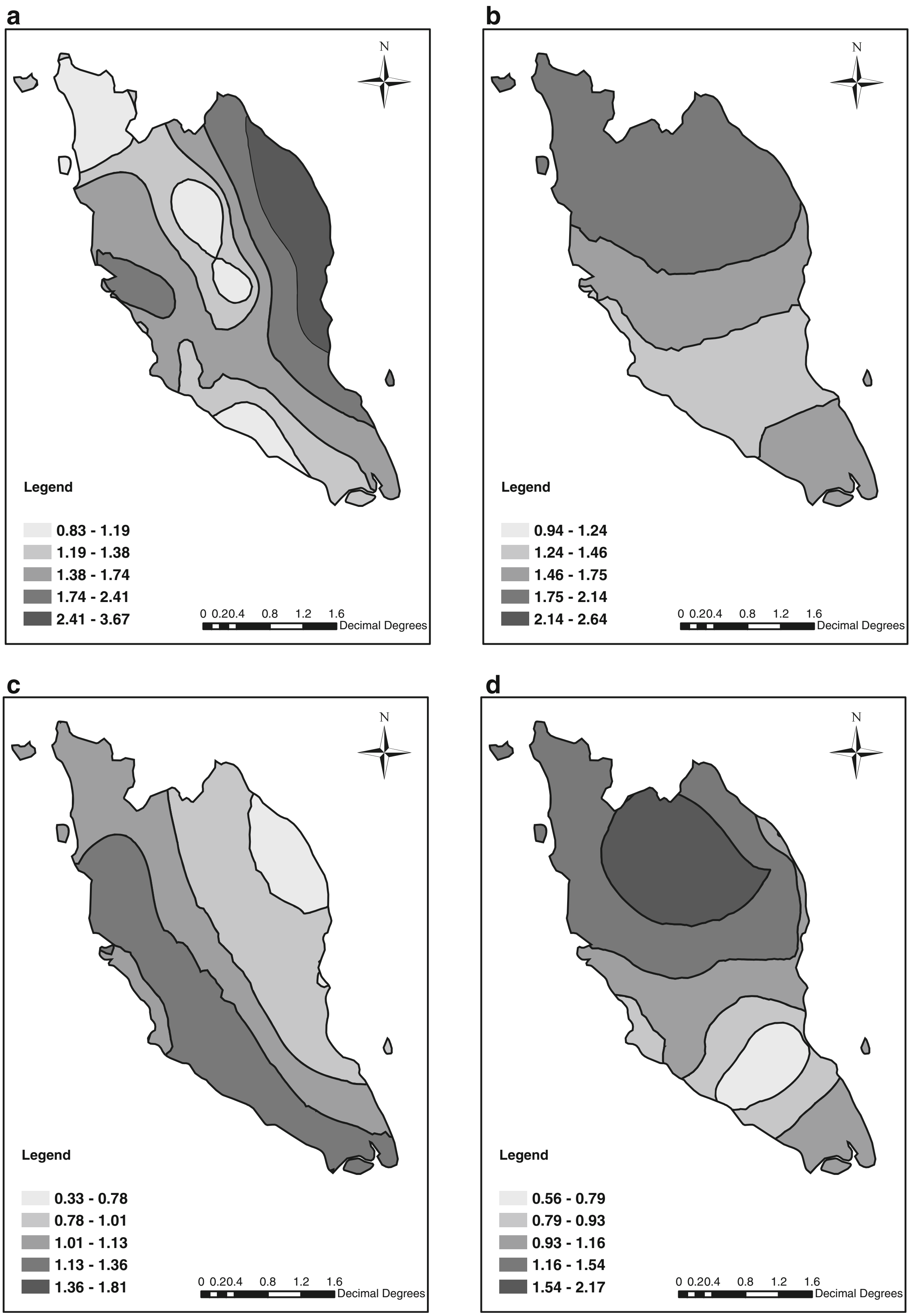

Fig. 9 Spatial distribution of total amount for Freq >99th index for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

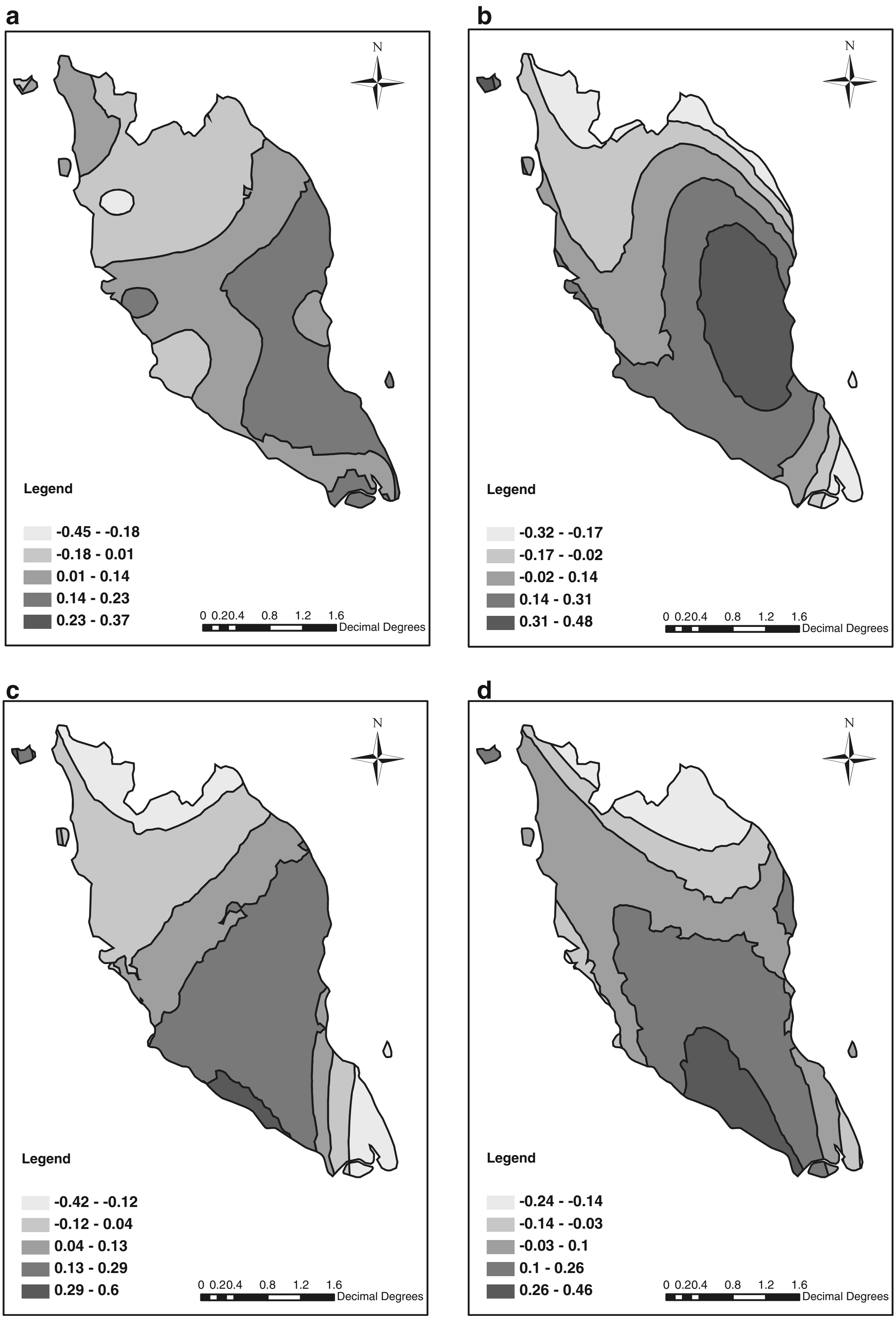

Fig. 10 Spatial pattern of trends for Hr Max for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

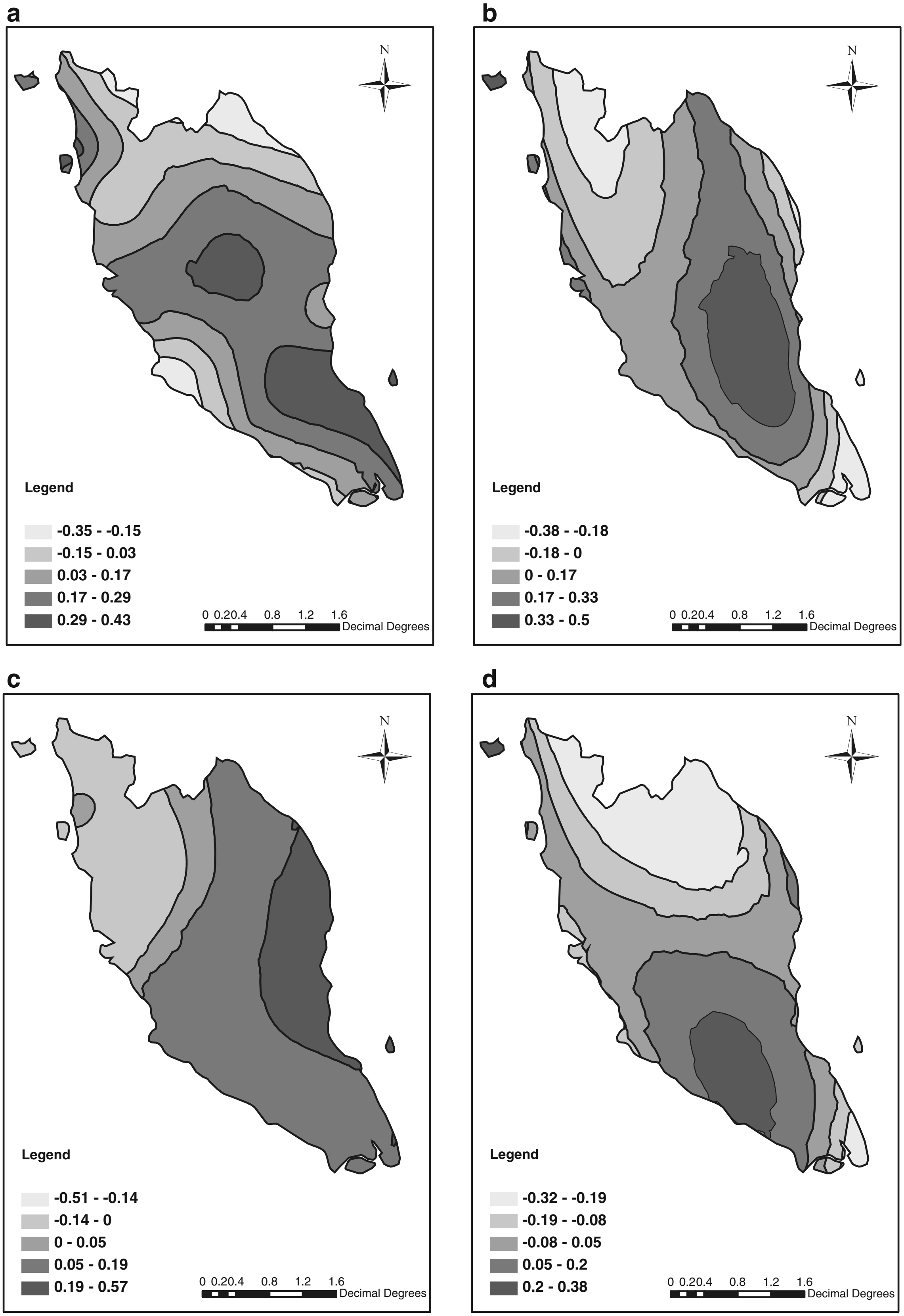

Fig. 11 Spatial pattern of trends for 5-Hr Max for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

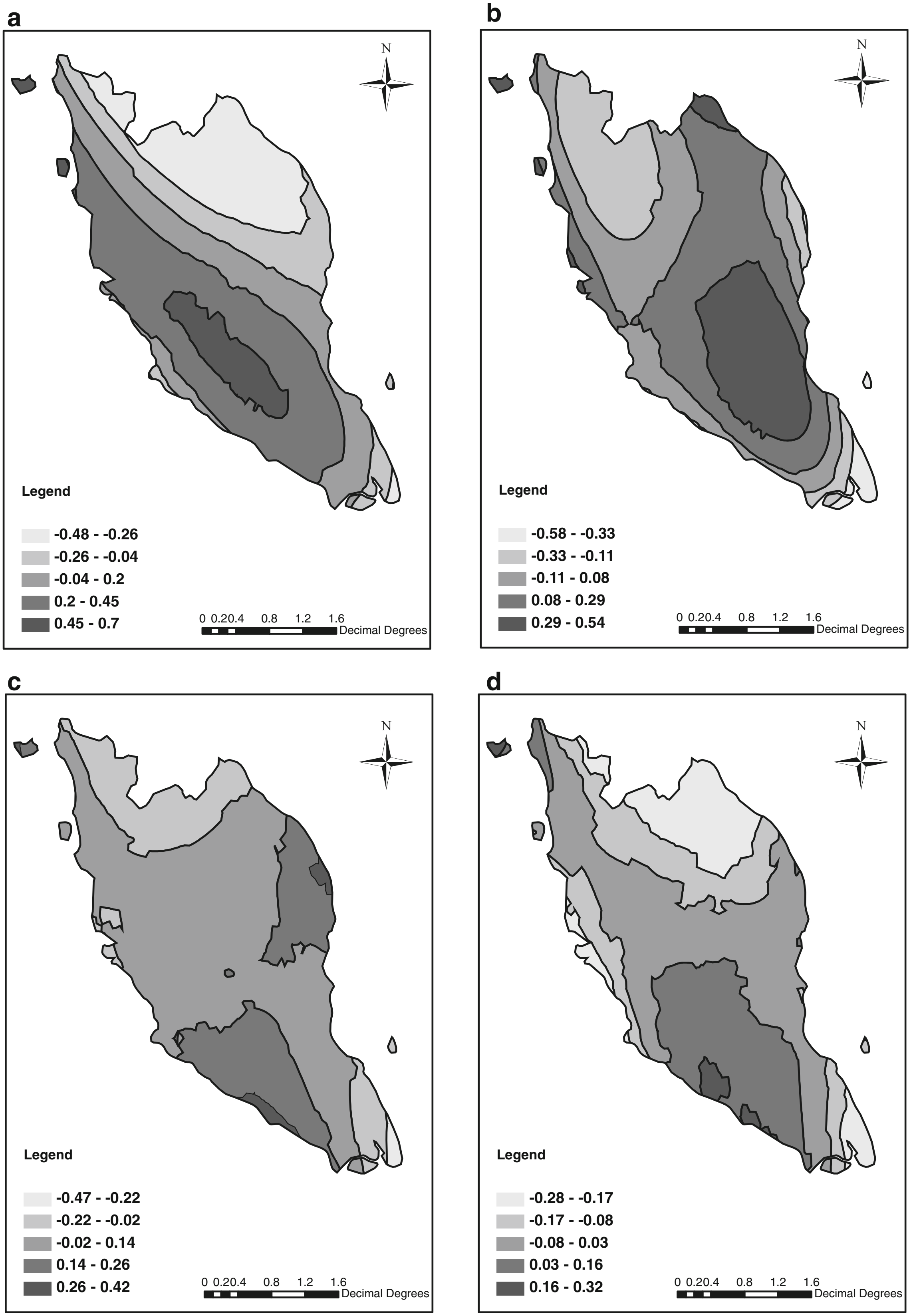

Fig. 12 Spatial pattern of trends for 24-Hr Max for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

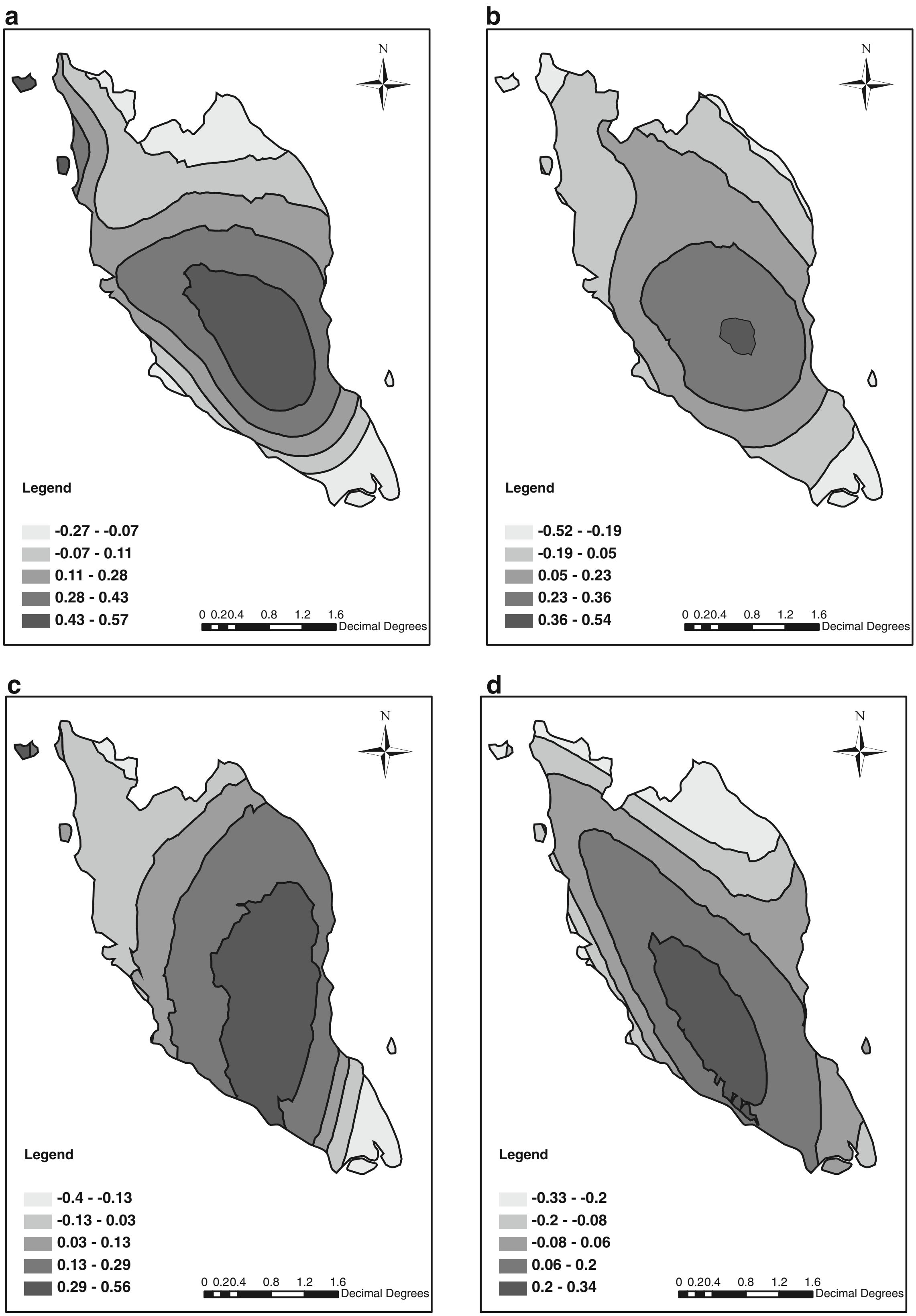

Fig. 13 Spatial pattern of trends for Tot >95th for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

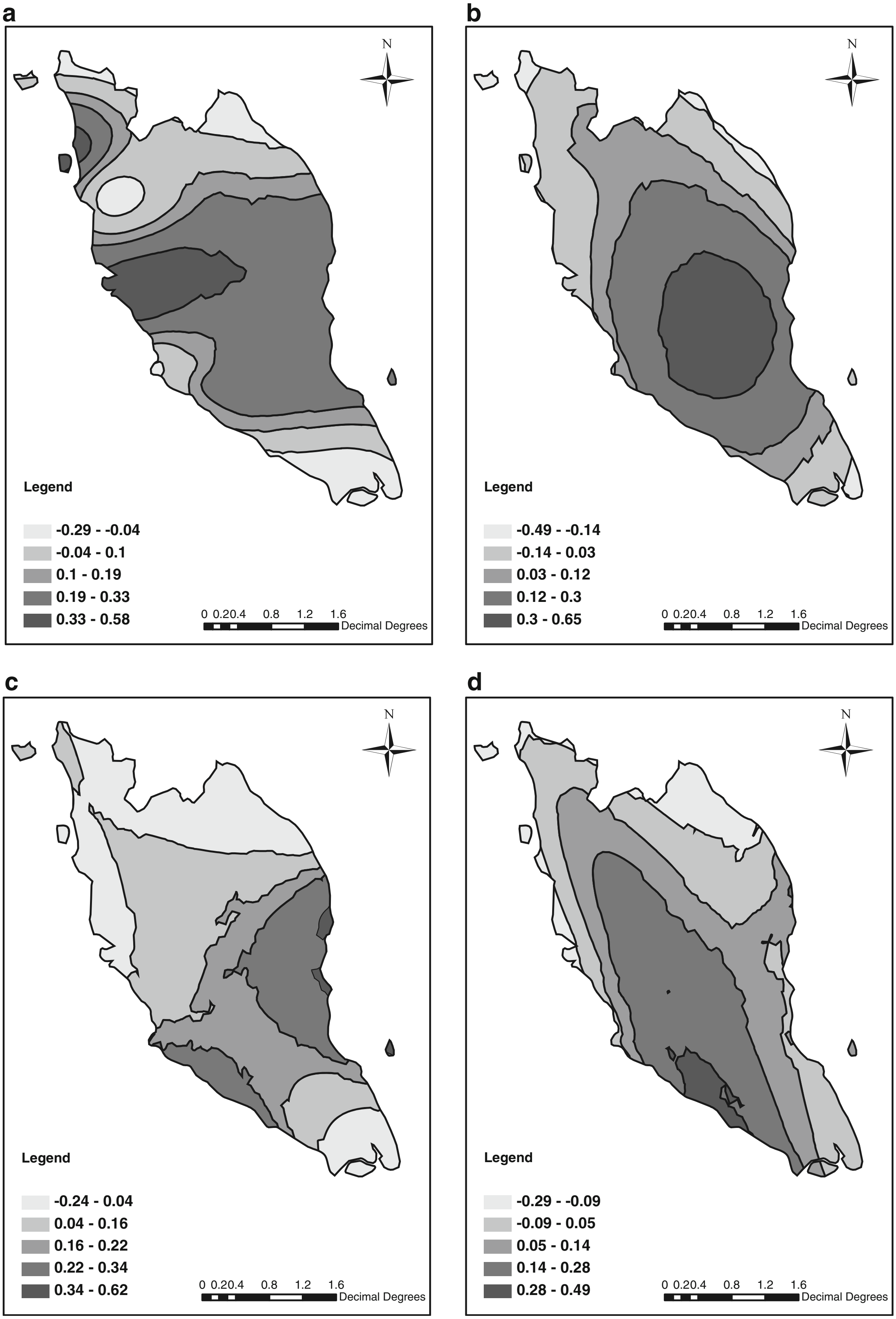

Fig. 14 Spatial pattern of trends for Tot >99th for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

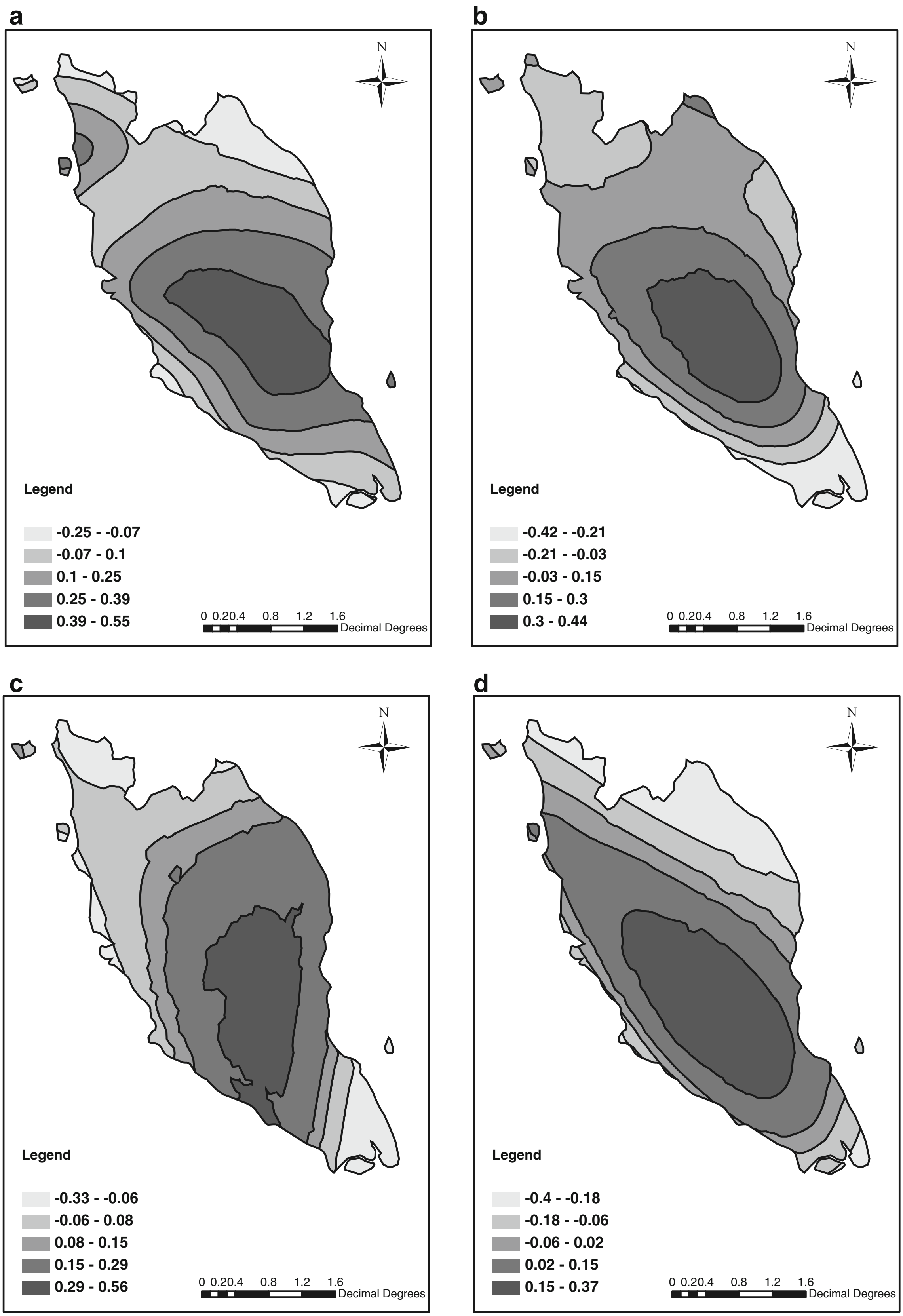

Fig. 15 Spatial pattern of trends for Freq >20 for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

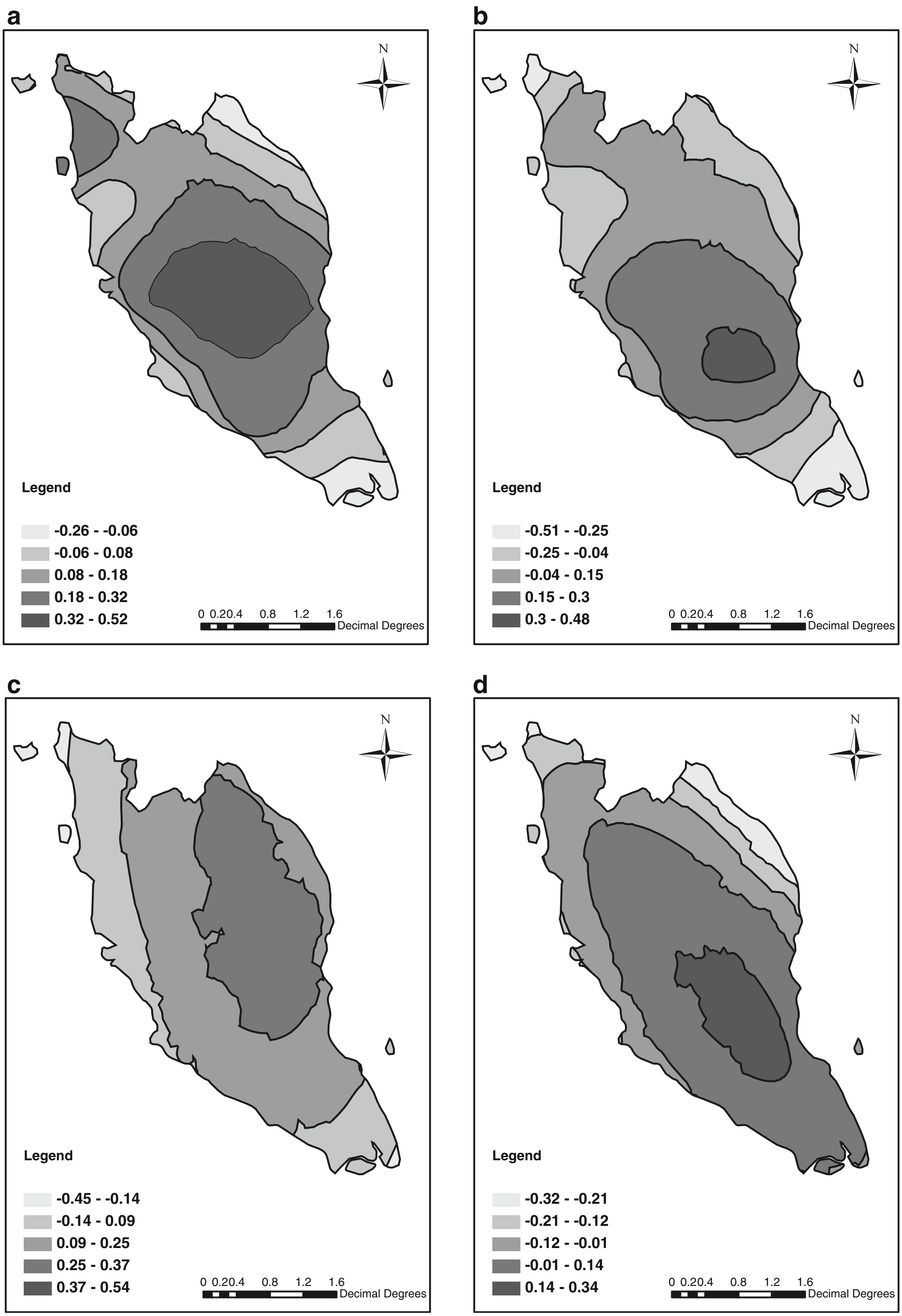

Fig. 16 Spatial pattern of trends for Freq >95th for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

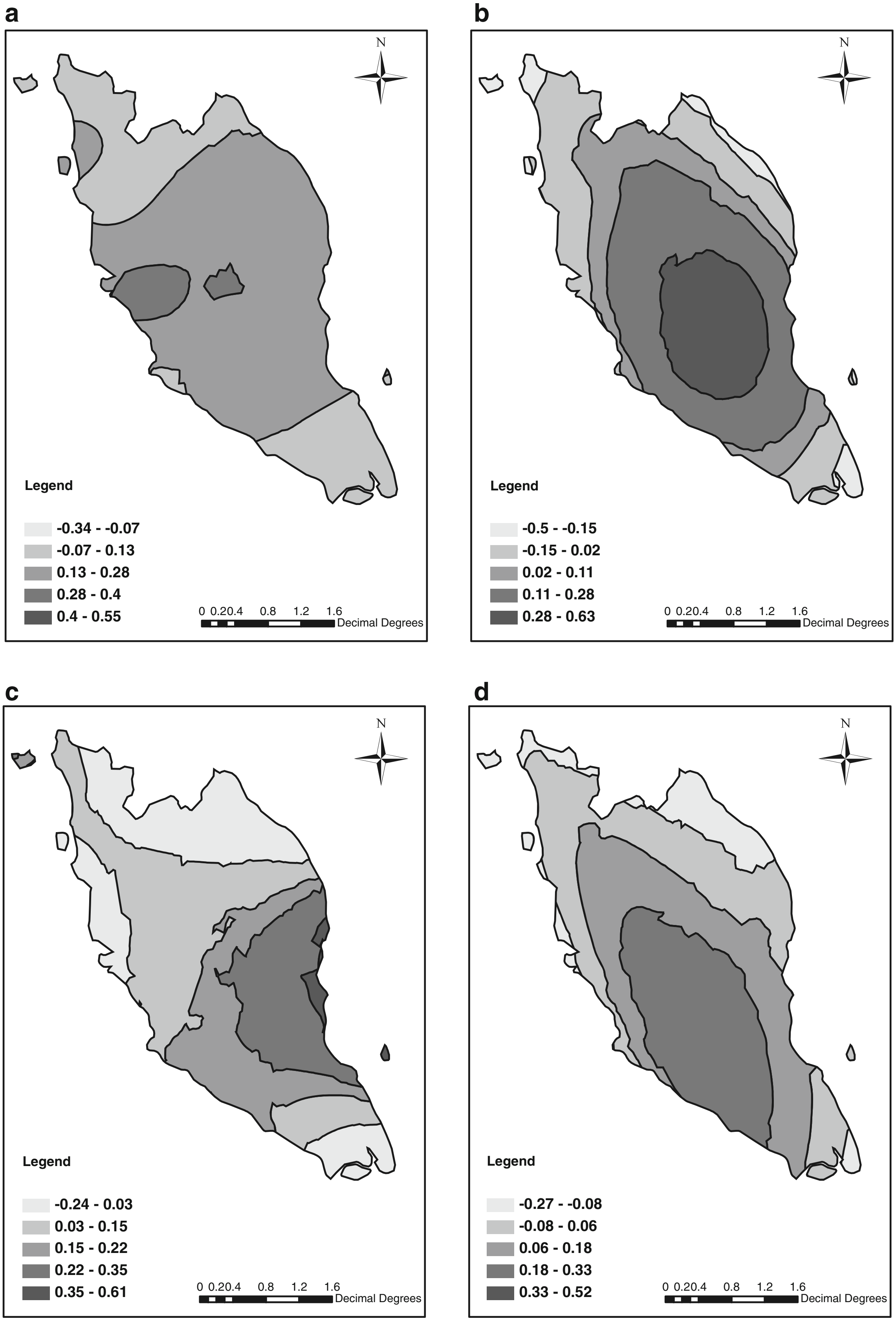

Fig. 17 Spatial pattern of trends for Freq >99th for **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) over 36 years (1975–2010)

north easterly winds. By comparing Hr Max and 24-Hr Max indices, it is shown that the western region experiences short duration extreme rainfall (Hr Max) during the NEM and MA but the eastern including some areas in the northwestern region experience long duration extreme rainfall (24-Hr Max) during the same seasons. Such results explain the occurrences of flash floods which frequently happen in urban areas (i.e., west coast) as well as massive floods in nonurban areas (i.e., east and northwest coasts).

It is also shown that the northern region experiences both short and long period of extreme rainfall during the SWM and SO. As for the Tot >95th and Tot >99th, NEM recorded the highest amount of rainfall that exceeds the 95th and 99th percentile throughout the 36 years followed by SWM and the inter-monsoon seasons. Monsoon seasons accumulate higher total amount of rainfall than inter-monsoon seasons due to monsoon seasons comprising of 4 months while inter-monsoon seasons comprising of 3 months. Similarly, the eastern region receives highest rainfall during the NEM while the western region receives highest rainfall during the MA. Furthermore, the northern region receives highest rainfall during the remaining seasons, SWM and SO. In relation to that, as the numbers of days for the four seasons are not the same, the extreme frequency indices will be compared between monsoon and inter-monsoon seasons (Figs. 7, 8, and 9). During the monsoon seasons, the extreme rainfall events frequently occurred during the NEM where the eastern region recorded the highest total amount of rainfall for the 95th and 99th percentile with amount of rainfall reaching up to 491.87 and 176.98 mm, respectively. During the inter-monsoon seasons, the extreme rainfall events frequently occurred during the SO where the northern region recorded the highest total amount of rainfall for the 95th and 99th percentile with amount of rainfall reaching up to 242.1 and 93.58 mm,

Table 3 Significant hourly extreme indices for each station during NEM

Station	Hr Max		5-Hr Max		24-Hr Max		Freq> 20		Freq> 95th		Tot> 95th		Freq> 99th		Tot> 99th	
	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
1737001					*											
2224038			*		*		*		*		*					
2719001															*	
2815001																
2818110																
2913001																
3117070					*		*		*		*					
3118102					*		*		*		*					
3314001																
3411017																
3516022																
3613004	*						*		*		*		*		*	
3710006	*		*				*		*		*		*		*	
4908018					*											
2831179	*		*		*		*		*		*		*		*	
3533102									*							
3924072																
4234109							*		*		*		*		*	
4734079																
4819027																
4930038																
5331048																
5504035	*		*				*		*		*		*		*	
6207032																
6401002																

"+" represents positive trend, "–" represents negative trend where darkened box represents significant trend for LS test, and "*" represents positive significant trend for MK test

respectively. As for the Freq >20, the frequency of rainfall events greater than 20 mm within 1 h is found to be higher during the NEM and MA for the each monsoon and inter-monsoon seasons.

4.2 Trend analysis of extreme rainfall indices

Figures 10, 11, 12, 13, and 14 illustrate the spatial pattern of trends for all extreme intensity indices for each season. The values represent the coefficient of trends of which positive sign indicates upward trend, whereas negative sign indicates downward trend. All the extreme intensity indices show similar pattern of trend where almost all regions show increasing trends during all seasons. The trends are more pronounced towards the southern part of peninsular. Negative trends are mostly in the northern region of the peninsular. Similarly, the extreme frequency indices (Figs. 15, 16, and 17) reveal upward trends in almost all regions during all seasons. Such trends are also more significant towards the southern part of peninsular during these seasons. The highest value of positive trend coefficient for Hr Max is observed for the MA (highest value of 0.6) while NEM has the lowest. In contrast, NEM has the highest value of positive coefficients of Freq >20, Freq >95th, and Tot >95th while SO has the lowest. Besides, SWM has the highest value of positive coefficients of Freq >99th and Tot >99th whereas SO has the lowest. As for the 5-Hr Max and 24-Hr Max, the highest value of positive coefficients are shown during MA and the NEM, respectively, of which both indices has the lowest positive value of coefficients during SO. Again by comparing Hr Max and 24-Hr Max, the short duration of extreme rainfall depicts an upward trend during MA while the long duration of extreme rainfall depicts

Table 4 Significant hourly extreme indices for each station during SWM

Station	Hr Max		5-Hr Max		24-Hr Max		Freq> 20		Freq> 95th		Tot> 95th		Freq> 99th		Tot> 99th	
	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
1737001																
2224038															*	
2719001	*		*		*		*		*		*		*		*	
2815001	*														*	
2818110																
2913001																
3117070	*												*		*	
3118102																
3314001																
3411017																
3516022							*		*		*		*		*	
3613004							*									
3710006																
4908018																
2831179	*		*		*		*		*		*		*		*	
3533102	*		*		*										*	
3924072															*	
4234109																
4734079																
4819027																
4930038																
5331048																
5504035			*		*		*				*		*		*	
6207032																
6401002																

"+" represents positive trend, "–" represents negative trend where darkened box represents significant trend for LS test, and "*" represents positive significant trend for MK test

the same trend during NEM over the years 1975–2010. Most of the extreme indices (total of six out of eight indices) has higher value of positive coefficients during the NEM and has the lowest during SO. Thus, it can be concluded that the positive trend of extreme rainfall over the years 1975–2010 is stronger during the NEM. This shows that the NEM brings increasing amount of rainfall compared to other seasons, hence the main contributing factor to the rainfall in Malaysia is the northeasterly winds over the South China Sea which is related to cold surges. The extreme rainfall in the west coast is also caused by strong pulses of west wind associated with the MJO, as it passes through the maritime continent (Salahuddin and Curtis 2011). In addition, six indices have shown higher value of positive coefficients during the monsoon seasons. This also proves that the positive trend of extreme rainfall is stronger during the monsoon seasons compared to the inter-monsoon seasons between the years 1975 and 2010.

4.3 The significant contribution of extreme indices to Malaysia's extreme rainfall

Tables 3, 4, 5, and 6 reveal the significant hourly extreme indices of each rainfall station using LS and MK test. In general, a large number of significant changes in extreme indices are found during the monsoon seasons that are the NEM and SWM, and this supports the findings discussed in Section 4.2. The analysis from MK test showed that all the significant extreme coefficients revealed upward trends. However, the results obtained between LS and MK tests are slightly different due to different approaches employed by both methods in analyzing the trends (Zin et al. 2010). Figure 18 depicts the significant trends of extreme rainfall indices for all seasons where the largest circle/triangle represents the largest contribution of extreme rainfall indices to the extreme rainfall trends. It shows that positive trends are more obvious during

Table 5 Significant hourly extreme indices for each station during MA

Station	Hr Max		5-Hr Max		24-Hr Max		Freq> 20		Freq> 95th		Tot> 95th		Freq> 99th		Tot> 99th	
	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
1737001																
2224038																
2719001	■ *		■ *				■ *		■ *		■ *		■ *		■ *	
2815001				■												
2818110																
2913001																
3117070																
3118102	■ *		*		■ *		■ *		■ *		■ *		*		■ *	
3314001																
3411017																
3516022																
3613004							*		*		*					
3710006																
4908018		■								■		■				
2831179	*						■ *		■ *		■ *					
3533102													■		■	
3924072						■										
4234109																
4734079	*		■ *		■ *		*		*		*		■ *		■ *	
4819027																
4930038																
5331048																
5504035	■ *		■ *		■ *		*		■ *		■ *				■ *	
6207032						■										
6401002																

"+" represents positive trend, "–" represents negative trend where darkened box represents significant trend for LS test, and "*" represents positive significant trend for MK test

Table 6 Significant hourly extreme indices for each station during SO

Station	Hr Max		5-Hr Max		24-Hr Max		Freq> 20		Freq> 95th		Tot> 95th		Freq> 99th		Tot> 99th	
	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
1737001																
2224038																
2719001	*						*						*		*	
2815001													*		*	
2818110	*		*				*		*		*		*		*	
2913001																
3117070	*		*								*		*		*	
3118102																
3314001																
3411017																
3516022	*												*		*	
3613004																
3710006																
4908018																
2831179	*		*				*		*		*		*		*	
3533102																
3924072																
4234109																
4734079																
4819027																
4930038																
5331048																
5504035	*		*				*		*		*					
6207032																
6401002																

"+" represents positive trend, "–" represents negative trend where darkened box represents significant trend for LS test, and "*" represents positive significant trend for MK test

the NEM while negative trends are more obvious during the SWM. The western region as well as the middle part of the peninsular experience more positive trends during the NEM, SWM, and MA while the northern region experiences more negative trends during the same seasons. Eighty percent of the significant extreme rainfall trends come from the monsoon seasons, i.e., NEM and SWM. In fact, 33 % relates to the NEM and SWM, while the rest 22 and 12 % are related to MA and SO, respectively. In general, 65 % of the indices show a positive trend of which 14 % are significant while the rest 35 % of the indices showed a negative trend of which only 4 % are significant. The field significance test showed that all extreme intensity, extreme cumulative, and extreme frequency indices revealed positive trends during the NEM and MA throughout Peninsular Malaysia over the years 1975–2010. However, only extreme intensity and extreme frequency revealed the same trends during the SWM and SO. In particular, Hr Max, Tot >95th, Tot >99th, Freq >99th, and 5-Hr Max showed upward trends during the SWM while other indices remain unchanged. Meanwhile, Hr Max, Tot >99th, and Freq >99th depicted the similar trends during the SO while other indices remain unchanged.

5 Conclusion

Analysis of extreme intensity indices shows higher values in the eastern region during the NEM while the western region depicts higher indices during MA. For the northern region, high indices were observed during the SWM and SO. However, short extreme intense rainfall (Hr Max) was observed mainly at stations located on the west coast where the hourly maximum was recorded during the inter-monsoon season while in contrast, extreme cumulative rainfall (24-Hr Max)

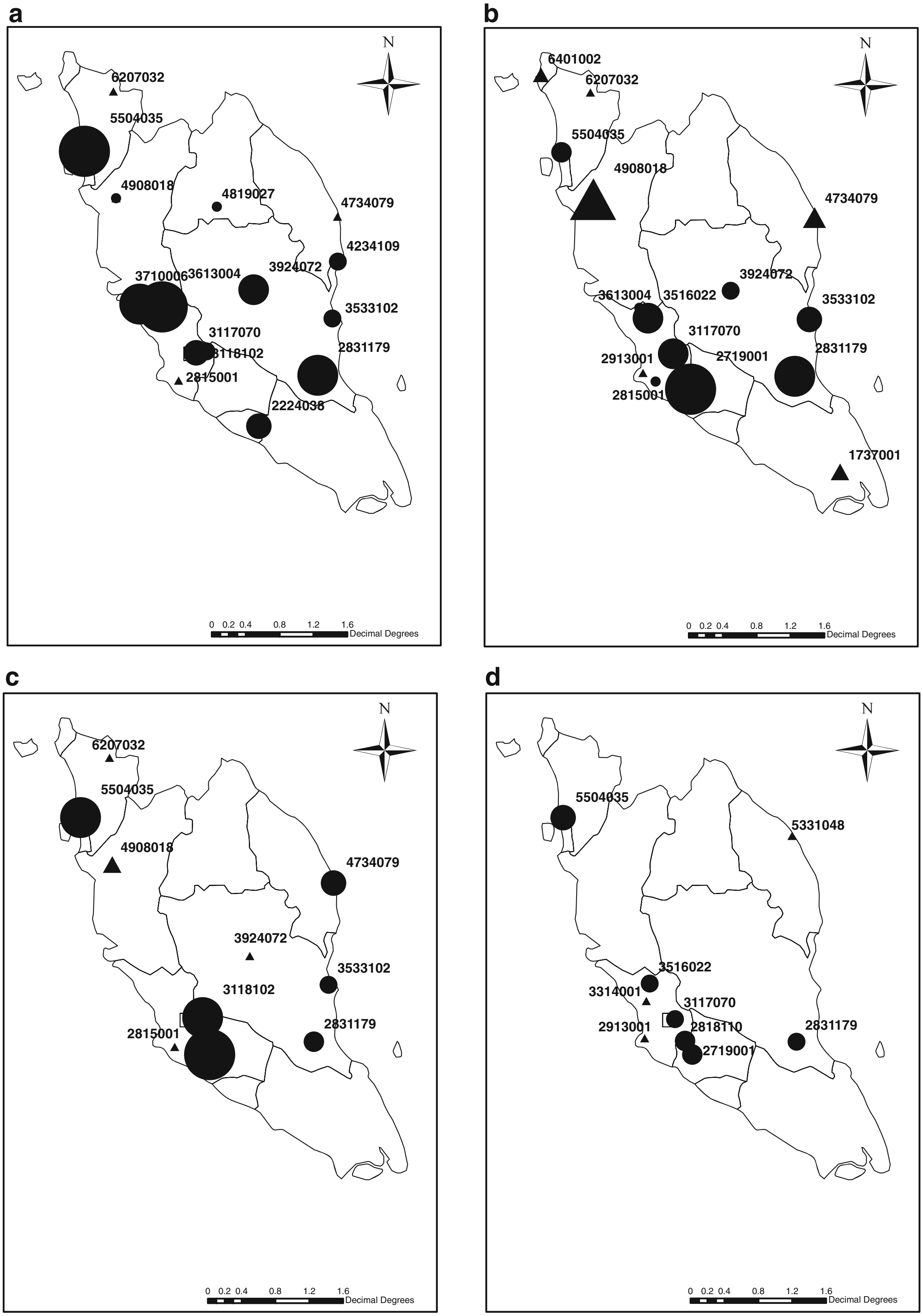

Fig. 18 Significant trends of extreme rainfall indices during **a** northeast monsoon season (*NEM*), **b** southwest monsoon season (*SWM*), **c** inter-monsoon season (*MA*), and **d** inter-monsoon season (*SO*) (*larger circle*/*triangle* indicates larger number of significant extreme rainfall indices where "*circle*" represents significant positive trend, "*triangle*" represents significant negative trend)

was observed at stations located on the eastern region where the highest value was recorded during the monsoon season. This shows that hourly data gives a better indication of the seasonal contribution to the annual extreme rainfall compared to daily data. It gives a better profile of the extreme indices with regards to short and long duration rainfalls.

From the spatial pattern of trend analysis, stations located on the western and southern stretch which comprises of mostly urban areas depict an increase in number of very wet and extremely wet hours. This explains the increase in the frequency of flash floods occurrences in these regions. Such analyses also conclude that the 95th percentile threshold is consistent with the 99th percentile threshold. However, northwest region experiences decrease in number of very wet and extremely wet hours. Thus, negative trend of extreme rainfall was found in the northwest region and can be considered as drier area. In addition to that, the extreme frequency index (Freq >20) gives more significant contribution to the positive extreme rainfall trend during the monsoon seasons. Meanwhile, both extreme frequency and extreme intensity (24-Hr Max, Freq >95th, Tot >95th, Tot >99th, and Hr Max) indices give more significant contribution to the positive extreme rainfall trend during the inter-monsoon seasons. It is also found that the highest number of very wet hours and extremely wet hours occur during the NEM which by large are produced by stratiform rain.

In summary, the field significance test proved that most of the significant extreme indices showed the positive sign of trends throughout Peninsular Malaysia mainly during the NEM and MA. Specifically, the extreme intensity, extreme frequency, and extreme cumulative indices showed increasing trends during the NEM and MA while extreme intensity and extreme frequency had similar trends during the SWM and SO. Overall, the hourly extreme rainfall events in Peninsular Malaysia showed an increasing trend between the years 1975 and 2010 with notable increasing trends in short temporal rainfall was observed during inter-monsoon season. Such result also shows that convective rain during this period contributes higher intensity rains which can only be captured using short duration rainfall series.

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