



# Trends analysis of rainfall and rainfall extremes in Sarawak, Malaysia using modified Mann–Kendall test

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## Abstract

This study assesses the spatial pattern of changes in rainfall extremes of Sarawak in recent years (1980–2014). The Mann–Kendall (MK) test along with modified Mann–Kendall (m-MK) test, which can discriminate multi-scale variability of unidirectional trend, was used to analyze the changes at 31 stations. Taking account of the scaling effect through eliminating the effect of autocorrelation, m-MK was employed to discriminate multi-scale variability of the unidirectional trends of the annual rainfall in Sarawak. It can confirm the significance of the MK test. The annual rainfall trend from MK test showed significant changes at 95% confidence level at five stations. The seasonal trends from MK test indicate an increasing rate of rainfall during the Northeast monsoon and a decreasing trend during the Southwest monsoon in some region of Sarawak. However, the m-MK test detected an increasing trend in annual rainfall only at one station and no significant trend in seasonal rainfall at any stations. The significant increasing trends of the 1-h maximum rainfall from the MK test are detected mainly at the stations located in the urban area giving concern to the occurrence of the flash flood. On the other hand, the m-MK test detected no significant trend in 1- and 3-h maximum rainfalls at any location. On the contrary, it detected significant trends in 6- and 72-h maximum rainfalls at a station located in the Lower Rajang basin area which is an extensive low-lying agricultural area and prone to stagnant flood. These results indicate that the trends in rainfall and rainfall extremes reported in Malaysia and surrounding region should be verified with m-MK test as most of the trends may result from scaling effect.

## 1 Introduction

Rainfall and temperature are often used as important climate parameters to determine the changes in global climate. According to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) (IPCC 2014), global temperature has increased in the

range of 0.65–1.06 °C over the period of 1880–2012. Across Southeast Asia, temperature has been increasing at the rate of 0.14–0.20 °C per decade since the 1960s, coupled with a rising number of hot days and warm nights, and a decline in cooler weather (Caesar et al. 2011; Manton et al. 2001; Tangang et al. 2007). It was noted that the increasing sea surface temperature due to climate change

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has caused the substantial changes in precipitation and precipitation extremes (Trenberth 2011). Spatial and temporal variability of climate plays a key role as a driver of many ecological and environmental processes because tropical regions are deemed to be more susceptible to climate change with significant regional heterogeneity particularly on the island of Borneo where Sarawak is located (Camera et al. 2016; Johnson 2012; Liu et al. 2009; Mishra et al. 2015). Furthermore, Southeast Asia is considered as one of the most vulnerable regions to climate change based on the Multiple Climate Hazard Index (Yusuf and Francisco 2009).

Located in the Maritime Continent, the changes of the rainfall trends in Sarawak were substantially influenced by the decadal, inter-annual and intra-seasonal large scale climate phenomena such as El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and Madden-Julian Oscillation (MJO) (Aldrian and Djamil 2008; Hidayat and Kizu 2010; Salahuddin and Curtis 2011). These large-scale phenomena are reflected in the long-term rainfall time series, which influence the annual, monsoon and extreme events variability in Sarawak. The ENSO is a coupled ocean-atmosphere phenomenon naturally occurring at the inter-annual time scale over the tropical Pacific, fluctuates between two states of El Niño and La Niña. In the years of El Niño, Sarawak is exposed to the risk of drier season and in the years of La Niña, exposed to the risk of heavy rains and floods. The IOD is defined by the difference in sea surface temperature between the western Indian Ocean and the eastern Indian Ocean south of Indonesia. A positive IOD event is often associated with El Niño and a negative event with La Niña. IOD develops in July–November changes in temperature gradients across the Indian Ocean which eventually affects convection over Sarawak and thus regional precipitation and temperature. The MJO is the dominant mode of tropical intra-seasonal variability, which contributes to intra-seasonal fluctuations of the monsoons in Sarawak (Zhang 2005; Maloney and Shaman 2008). An equatorial region like Sarawak is also affected by the inter-tropical convergence zone (ITCZ). As the ITCZ passes over these areas, it brings two periods of very heavy rainfall every year. One occurs when the ITCZ crosses these areas on its way north and another occurs when it crosses these areas again on its way south.

Numerous studies have been conducted on the trend of the rainfall on different spatial and temporal scales to assess the potential impacts of climatic change and variability (Mayowa et al. 2015; Abolverdi et al. 2016; Gao et al. 2016; Ongoma and Chen 2016; Rahman et al. 2016; Xiao et al. 2016). The studies indicate that global warming has reformed precipitation resulting in frequent extreme weather events and risks (Pour et al. 2014; Sung et al. 2015; Bari et al. 2016; Wang et al. 2016). According to the IPCC, global

precipitation is subject to increase with extreme precipitation events over most of the wet tropical region and will likely become more intense and more frequent in the future (IPCC 2014). For the Southeast Asia region, Endo et al. (2009) found that the heavy precipitation indices, which are defined by a precipitation amount and percentile, demonstrate the significant upward trend at more stations compared to the significant downward trend between 1950s and 2000s. The number of a rainy day is also found to significantly decrease throughout most of the countries of Southeast Asia between 1961 and 1998 (Manton et al. 2001).

In Malaysia, several studies have been conducted to investigate the behavior and trend in various rainfall indices (Varikoden et al. 2011; Suhaila et al. 2011; Hamdan et al. 2012; Dindang et al. 2013; Othman et al. 2015; Sang et al. 2015). Sang et al. (2015) analyzed the long-term trends of consecutive dry and wet days and extreme rainfall amounts in Malaysia and showed an increase in extreme rainfall amounts in most parts of the country where the Malaysia Peninsula and Sarawak has been getting increased maximum consecutive dry spells durations while Sabah has been seeing increased maximum continuous wet spells. Dindang et al. (2013) conducted the rainfall trend analysis in Kuching, Sarawak for the period 1968–2010 using regression linear analysis and Mann-Kendall (MK) test, and finds that in overall, there were no statistical significant trend for annual and monthly rainfall. Hamdan et al. (2012) determined the relationship of the Southern Oscillation Index (SOI) on Sarawak during Northeast (NE) monsoon and found that only Miri meteorological station are vulnerable to SOI. Previous studies mainly attempted to assess rainfall trend, focusing in Malaysia Peninsula while only selected region and limited number of stations was being investigated to understand the climate pattern and trend of the whole region of Sarawak in Malaysia. Therefore, it is in our interest to investigate the rainfall trends which covering the whole region of Sarawak using long-term rainfall record to understand the spatial and temporal variation of the annual, seasonal and extreme rainfall events.

A variety of statistical methods broadly categorized as parametric and non-parametric have been applied to detect trends and other changes in hydrology and climatic variables in previous studies (Deni et al. 2009, 2010; Jha and Singh 2013; Othman et al. 2015; Suhaila et al. 2011; Suhaila and Jemain 2009). Parametric methods assume an underlying normal distribution for the variables of interest and need to satisfy both distributional and independent assumptions, whereas non-parametric methods have neither fixed parameters nor distribution and only has the need to satisfy the independent assumption (Sonali and Kumar 2013). Non-parametric Mann-Kendall method has been widely used for trend tests in recent years because it does not require the datasets to be normally distributed and has low sensitivity

to abrupt breaks due to inhomogeneous time series (Yue and Wang 2004; Shahid 2010). The only requirement of the trend tests is that the data should be independent, but the positive serial autocorrelation in the data will increase the chance for significance in trend. The effect of autocorrelation should be eliminated either by removing serial correlation of the data before applying trend tests, or by modifying the original trend tests to account for serial correlation (Hamed 2008). Yue and Wang (2002) used “pre-whitening” of the data, where serial correlation was first removed and then the trend tests were performed on the uncorrelated residuals. On the other hand, Hamed and Rao (1998) and Yue and Wang (2004) introduced modified Mann–Kendall (m-MK) trend tests to account for the effect of a serial correlation.

Besides autocorrelation, the significance of the hydroclimatic trends over time is very sensitive to the assumptions about whether the underlying data have a short-term or long-term persistence (LTP). Most of the studies on the rainfall trend analysis in Malaysia and other parts of the world used standard MK tests over 30–50 years of climate data, considering that natural variability alters the climate pattern on time scales shorter than 30 years (McMichael et al. 1996). However, recent analysis of multi-centennial time series data reveal that wet or dry periods exceeding 50 years can exist (Lacombe et al. 2012). It has been reported that long-term persistence or Hurst phenomenon can lead to a considerable reduction in significance of trends (Hamed 2008). Koutsoyiannis and Montanari (2007) reported that Mann–Kendall trend tests statistic is greatly affected by the scaling behavior. Therefore, a number of recent studies cast doubt on the results that was previously obtained due to multi-decadal variability (Kumar et al. 2009; Ehsanzadeh and Adamowski 2010; Lacombe et al. 2012; Shahid et al. 2014; Fathian et al. 2015). Hamed (2008, 2009) modified the MK method to account for the scaling effect, thus enhancing the ability of the tests to discriminate multi-scale variability of unidirectional trends of the rainfall indices. Thus, the m-MK tests are also used in the present study to confirm the significance of MK tests for rainfall extremes in Sarawak.

In recent years, increased events of extreme rainfall leading to the inland and coastal flooding, landslides, and agricultural damages have been reported in Sarawak (Gasim et al. 2014). For example, two heavy rainfall episodes in early 2011 caused severe floods that almost covered the whole region of Sarawak (Dindang et al. 2011). In December 2014 and January 2015, another heavy rainfall occurred almost throughout Sarawak, where in particular a high intensity rainfall of over 250 mm of rainfall fell in Kuching between 18 and 19 January 2015 caused major flood disaster forcing the people to be evacuated. These events have raised a concern for promoting further research on analyzing the rainfall trend and behavior, particularly on rainfall extremes

to investigate whether these changes are of concern and statistically significant.

## 2 Study area and data

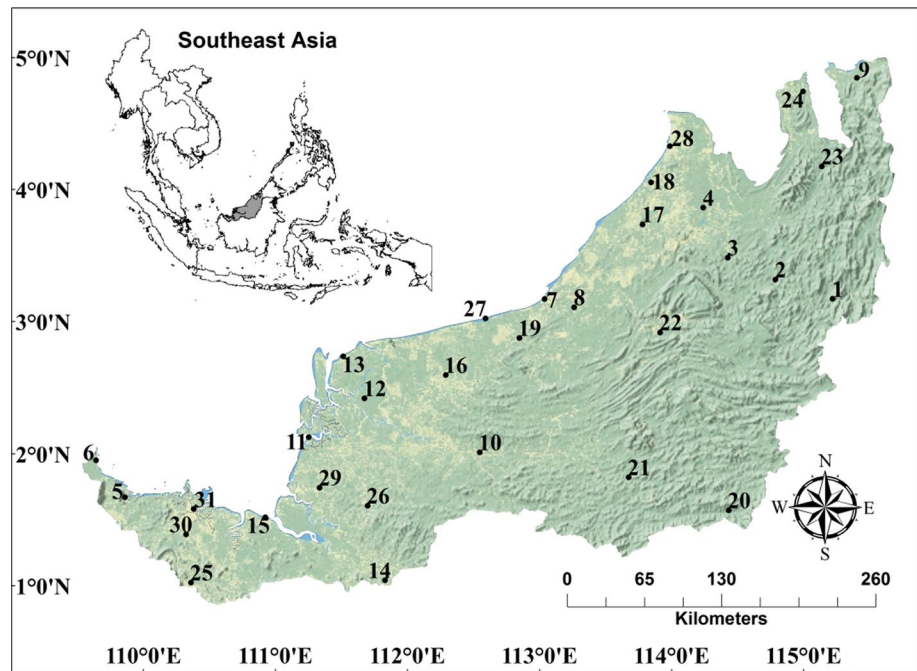
### 2.1 Study area

Sarawak with an area of 124,450 km<sup>2</sup> stretches over some 700 km along the northwestern coast of the island of Borneo (latitude 0°50′–5°N and longitude 109°36′–115°40′) (Fig. 1). The region has an equatorial climate characterized by uniform temperature, high humidity and copious rainfall. The Köppen–Geiger climate classification of this region is a Tropical Rainforest with annual rainfall ranging between 3300 mm near the coastland to 4600 mm in further inland (Kottek et al. 2006). Daily temperature ranges from 23 °C in the early morning to 32 °C at noon. Humidity is constantly high and usually exceeding 68% throughout the year. Owing to the geographic location, Sarawak experiences two monsoons which are influenced by seasonal wind flow, namely, NE monsoon (November–March) and Southwest (SW) monsoon (May–September), and two short inter-monsoon seasons in April (Int-Aprl) and October (Int-Oct). The NE monsoon is the wettest period characterized by the steady easterly or northeasterly winds of 10–20 knots while the SW monsoon is relatively dry, characterized by light south westerly wind (below 15 knots) (Dindang et al. 2013; Yik et al. 2015). The NE monsoon is more prominent because of the sudden surge in the rainfall amounts while the SW monsoon is associated with a relatively dry period during the active monsoon months (Dindang et al. 2013; Yik et al. 2015). However, the seasonal cycle of the monsoon in Sarawak has shown spatial and temporal variations due to the complex distribution of land, sea and terrain (Chang et al. 2005). According to Yik et al. (2015), the rainfall over Sarawak shows a different regime from that found in Malaysia Peninsula where there is only one peak in the rainfall distribution prominently along the coastal region.

### 2.2 Data and sources

Trends based on shorter time series are very sensitive to the values at the beginning and at the end of the series. Thus, it cannot generally reflect long-term climate trends. Therefore, a long-term statistical trend analysis of observation data which show the changes in weather patterns over the decades is employed to identify the rainfall trend. Hourly rainfall data recorded at 31 rainfall stations being distributed fairly throughout Sarawak for a period 1980–2014 were obtained from the Drainage and Irrigation Department of Malaysia. The rainfall data have been summed into monthly, seasonal and annual totals to calculate the extreme rainfall events.

**Fig. 1** Location of rainfall stations in the map of Sarawak



Description of stations is given in Table 1 and the locations of all stations are shown in Fig. 1. However, it must be noted that the meteorological stations were not fairly distributed and period of rainfall records are not sufficient to monitor a longer historical rainfall pattern throughout the large area of Sarawak. There is also a problem with the unavailability of long-term data for some of the stations and the need to consider the amount of missing data. Therefore, some stations were excluded owing to missing data spanning several years. The subjective double mass curve method and the objective student's *t* test were applied to the annual precipitation time series of each station to assess the quality of rainfall record. The double mass curve showed no breakpoint in the time series of precipitation. The sequential Student's *t* test revealed no statistically significant variation or break point existing in the rainfall time series.

### 3 Methodology

MK and m-MK trend tests were used to assess the significance of the change and the Sen's slope method was used to estimate the rate of change in the rainfall indices. The methods are described below.

#### 3.1 MK and m-MK trend test

In MK trend tests (Mann 1945; Kendall 1948), each value is compared to all subsequent data i.e., the ordered data sample. Mann–Kendall statistic (*S*) for a time series  $x_1, x_2, x_3, \dots$ , and  $x_n$  is calculated as,

$$S = \sum_{k=1}^{n-1} \sum_{i=k+1}^n \text{sign}(x_i - x_k),$$

$$\text{where sign}(x_i - x_k) = \begin{cases} +1 & \text{if } (x_i - x_k) > 0 \\ 0 & \text{if } (x_i - x_k) = 0 \\ -1 & \text{if } (x_i - x_k) < 0 \end{cases} \quad (1)$$

The probability associated with *S* and the sample size, *n*, is then computed to statistically quantify the significance of the trend using normalized test statistic *Z* as follows:

$$\text{where sign}(x_i - x_k) = \begin{cases} +1 & \text{if } (x_i - x_k) > 0 \\ 0 & \text{if } (x_i - x_k) = 0 \\ -1 & \text{if } (x_i - x_k) < 0 \end{cases} \quad (2)$$

The variance is computed as

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18}, \quad (3)$$

where *n* is the number of data points, *m* is the number of tied groups and  $t_i$  denotes the number of ties of extent *i*. A tied group is a set of sample data having the same value. A positive or negative value of *Z* indicates an upward or downward trend. At the 95% significance level, the null hypothesis of no trend is rejected if  $|Z| > 1.96$ ; and at the 90% significance level, the null hypothesis of no trend is rejected if  $|Z| > 1.645$ .

**Table 1** List of rain gauges and period of data used

Sta. no.	Area charac.	Basin	Elev (m)	Period	Ann rain (mm)	Sta. no.	Area charac.	Basin	Elev (m)	Period	Ann rain (mm)
1	B, D	Baram	265	1987–2014	4228	17	B, C	Niah	35	1985–2014	2892
2	B, D	Baram	106	1983–2014	4390	18	A, C	Sibuti	9	1984–2014	2453
3	B, D	Baram	57	1983–2014	3788	19	B, C	Tatau	13	1985–2014	3568
4	B, C	Baram	17	1983–2014	3115	20	B, D	U. Rajang	355	1982–2014	4385
5	A, C	Kayan	38	1983–2014	3603	21	B, , D	U. Rajang	253	1983–2014	4778
6	B, C	Kayan	23	1983–2014	3416	22	B, D	U. Rajang	260	1984–2014	4108
7	A, C	Kemena	16	1973–2014	3755	23	B, D	Limbang	206	1984–2014	2947
8	B, C	Kemena	15	1984–2014	3231	24	A, C	Limbang	16	1984–2014	3255
9	A, C	Lawas	34	1989–2014	3610	25	B, D	Sadong	70	1983–2014	3067
10	A, C	L. Rajang	44	1983–2014	3208	26	B, D	Saribas	218	1983–2014	3574
11	B, C	L. Rajang	6	1986–2014	3144	27	B, C	Balingian	3	1979–2014	3659
12	B, C	L. Rajang	27	1986–2014	3092	28	B, C	Baram	18	1982–2014	2672
13	B, C	L. Rajang	10	1984–2014	3266	29	A, C	Krian	9	1984–2014	3173
14	A, D	Lupar	72	1984–2014	3264	30	A, C	Samarahan	60	1982–2014	3815
15	B, C	Lupar	1	1984–2014	3631	31	A, C	S. Sarawak	5	1977–2014	3706
16	B, C	Mukah	18	1990–2014	3422						

*St no* station number, *A* urban, *B* non-urban, *C* coastal and/or low-lying, *D* interior and/or high elevation areas, area charac area characteristic, *elev* elevation, *ann rain* annual rainfall, *L. Rajang* Lower Rajang, *U. Rajang* Upper Rajang, *S. Sarawak* Sungai Sarawak

In m-MK tests, the equivalent normal variants of rank of the de-trended series are obtained using the following equation:

$$Z_i = \phi^{-1} \left( \frac{R_i}{n+1} \right) \quad \text{for } i = 1 : n, \tag{4}$$

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

The scaling coefficient or Hurst coefficient,  $H$  is obtained by maximizing log likelihood function in McLeod and Hipel (1978). This estimate of  $H$  is approximately normally distributed for the uncorrelated case when true  $H$  is 0.5. The correlation matrix for a given Hurst coefficient,  $H$  is derived using the following equation:

$$C_n(H) = [\rho_{|j-i|}], \quad \text{for } i = 1:n, j = 1:n, \tag{5}$$

$$\rho_l = \frac{1}{2} (|l+1|^{2H} - 2|l|^{2H} + |l-1|^{2H}), \tag{6}$$

where  $\rho_l$  is the autocorrelation function of lag  $l$  for a given  $H$ , and is independent of the time scale of aggregation for the time series (Koutsoyiannis 2003). The value of  $H$  is obtained by maximizing the log likelihood function of  $H$  as given below

$$\log L(H) = -\frac{1}{2} \log |C_n(H)| - \frac{Z^T [C_n(H)]^{-1} Z}{2\gamma_o}, \tag{7}$$

where  $|C_n(H)|$  is the determinant of correlation matrix  $[C_n(H)]$ ,  $Z^T$  is the transpose vector of equivalent normal variates  $Z$ ,  $[C_n(H)]^{-1}$  is the inverse matrix, and  $\gamma_o$  is the variance of  $z_i$ . Equation (7) can be solved numerically for different values of  $H$ , and the value for which  $\log L(H)$  is maximum is taken as the  $H$  value for the given time series  $x_i$ . In this study, the value of  $H$  is solved between 0.50 and 0.98 with an incremental step of 0.01.

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

$$\begin{aligned} \mu_H &= 0.5 - 2.87n^{-0.9067}, \\ \sigma_n &= 0.7765n^{-0.5} - 0.0062. \end{aligned} \tag{8}$$

The significance of  $H$  is determined using  $\mu_H$  and  $\sigma_n$  in Eq. (8). In this study, 5 and 10% significance levels were used for rainfall to determine the significance of  $H$ . The Hurst coefficient provides a measure for long term memory or persistence in the series. In this study, the method proposed by Hamed (2008) was used to find the significance of

$H$  value. If  $H$  is found to be significant, the variance of  $S$  is calculated using the following equation for given  $H$ :

$$V(S)^{H'} = \sum_{i < j} \sum_{k < l} \frac{2}{\pi} \sin^{-1} \left( \frac{\rho|j-i| - \rho|i-l| - \rho|j-k| + \rho|i-k|}{\sqrt{(2-2\rho|i-j|)(2-2\rho|k-l|)}} \right), \tag{9}$$

where  $\rho_l$  is calculated using Eq. (6) for given  $H$  and  $V(S)^{H'}$  is the biased estimate. The unbiased estimate  $V(S)^H$  is calculated by multiplying by a bias correcting factor  $B$  as below

$$V(S)^H = V(S)^{H'} \times B, \tag{10}$$

where  $B$  is a function of  $H$  as below

$$B = a_0 + a_1H + a_2H^2 + a_3H^3 + a_4H^4 \tag{11}$$

The coefficients,  $a_0, a_1, a_2, a_3,$  and  $a_4$  in Eq. (11) are functions of the sample size  $n$ . The values of the coefficients can be found in Hamed (2008). The significance of the MK test is computed using  $V(S)^H$  in place of  $V(S)$  in Eq. (2). Details of m-MK method can be found in Hamed (2008).

### 3.2 Sen's slope estimator

Sen's slope estimator (Sen 1968) has been widely used in hydro-meteorological time series for estimation of the slope or rate of change (Bari et al. 2016; Lu et al. 2016; Thomas and Prasannakumar 2016). To derive an estimate of the slope  $Q$ , the slopes of all data pairs are calculated,

$$Q_i = \frac{x_j - x_k}{j - k}, \quad i = 1, 2, \dots, N, \quad j > k. \tag{12}$$

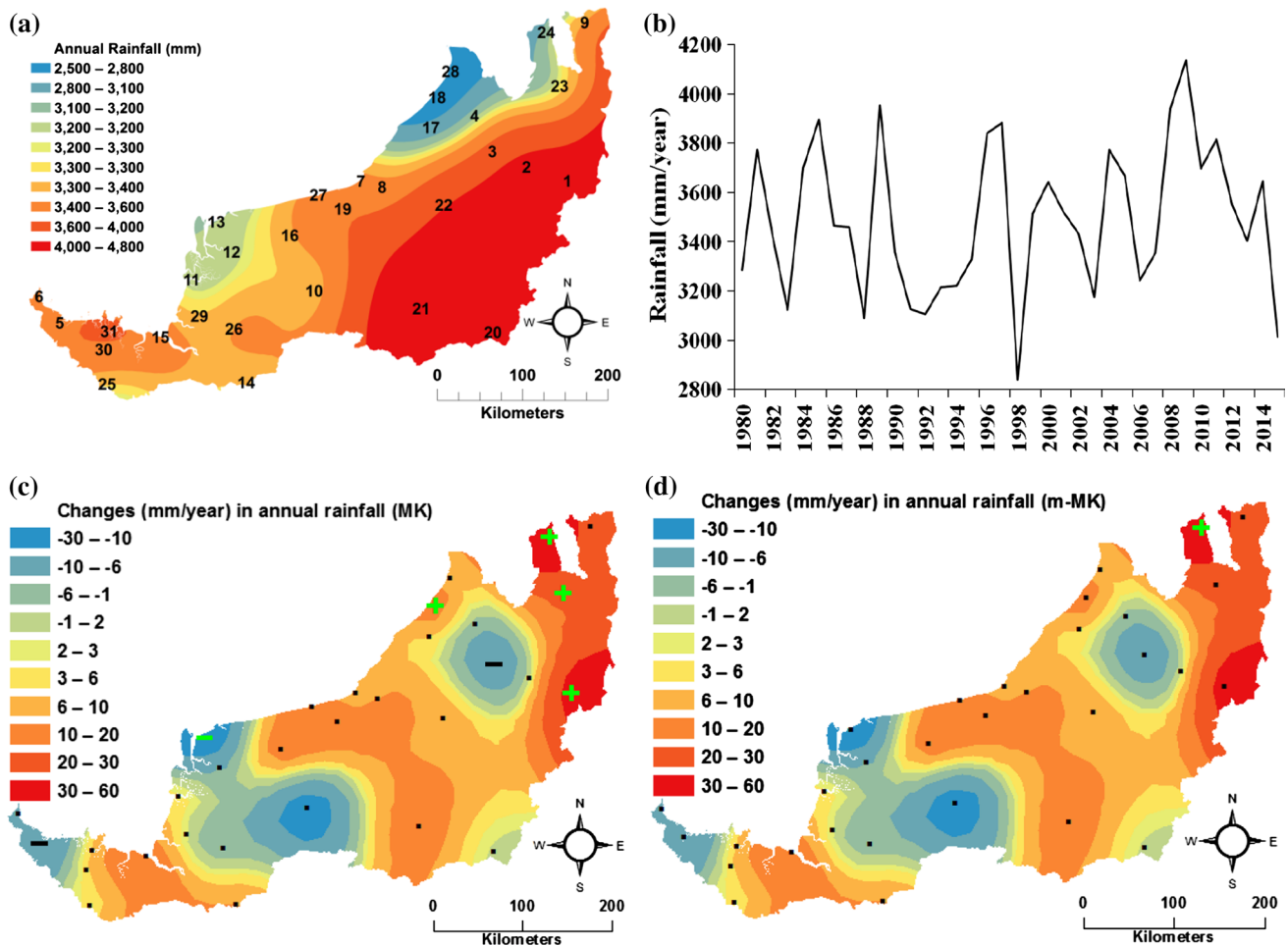
If there are  $n$  values in the time series, we get as many as  $N = n(n - 1)/2$  slope estimates  $Q_i$ . The Sen's estimator of slope is the median of these  $N$  values of  $Q_i$ . The  $N$  values of slopes are ranked from the smallest to the largest and the Sen's estimator is the median of all slopes,

$$Q_{\text{med}} = \begin{cases} Q_{|(N+1)/2|} & \text{if } N \text{ is odd} \\ \frac{Q_{|N/2|} + Q_{|(N+2)/2|}}{2} & \text{if } N \text{ is even} \end{cases}. \tag{13}$$

## 4 Results

### 4.1 Annual rainfall analysis

Spatial distribution and temporal variability of annual rainfall in Sarawak are shown in Fig. 2a, b, respectively. Figure 2a shows that annual average rainfall of Sarawak varies from 2458 mm near the coastland to 4800 mm in further inland. The time series of annual rainfall (Fig. 2b) shows that the mean annual rainfall in the region is 3571.8 mm with the maximum rainfall recorded in 2009 (4136.2 mm) while the minimum rainfall recorded in 1998 (2838.6 mm). The result was in conjunction with the years 2007–2008 recorded as



**Fig. 2** a Spatial distribution of mean annual rainfall (mm/year); b time series of mean annual rainfall average for all stations; and trends in mean annual rainfall (mm/year) for the period of 1980–2014

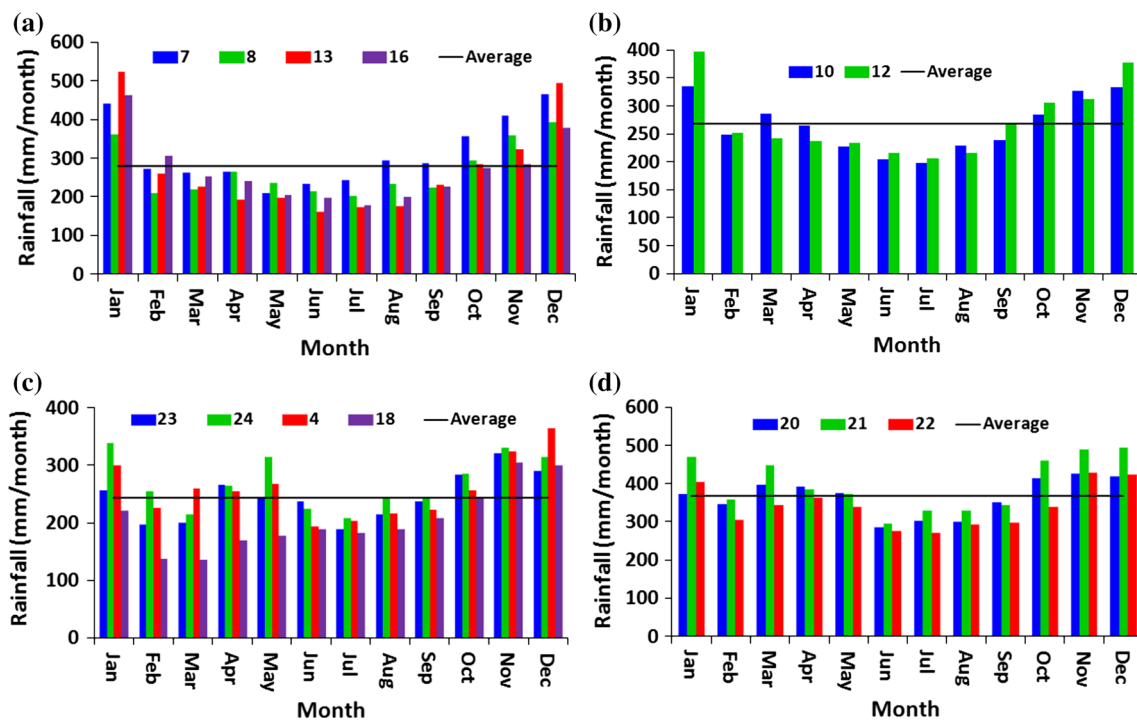
detected using c MK; and d m-MK trend tests where (+) and (–) denotes increasing and decreasing rainfall at 90% (black) and 95% (green) confidence levels

the strongest La Niña since 1989, whereas the strongest El Niño occurs in 1997–1998 other than 1982–1983 (Hamdan et al. 2012). Figure 2c, d show the trends in mean annual rainfall in Sarawak for the period of 1980–2014 detected by MK and m-MK trend tests. The rates of change estimated using the Sen's slope method at 31 stations were interpolated using Kriging method using geographical information system (GIS) software ArcMap version 10.2 to show the spatial pattern of annual rainfall trends in Sarawak. The maps show that the MK trend test detected a significant change in annual rainfall in 7 out of the 31 stations at 90% significance level with increasing at 4 stations located mostly in the northwest region at a rate of above 30 mm/year and decrease at 3 stations of different regions at a rate of 20 mm/year. However, the m-MK test detected an increasing trend only at one station located in northwest corner of Sarawak. By taking account of the scaling effect through eliminating the effect of autocorrelation, m-MK was capable to discriminate multi-scale variability of the unidirectional trends of the annual

rainfall in Sarawak. It can confirm the significance of the MK test. The results indicate that most of the significant changes in annual rainfall trends detected by the MK test result from the ignorance of scaling effect. After considering LTP in trend analysis, no significant decrease in annual rainfall at any stations of Sarawak and the increase at only one station located in northwest Sarawak at the 95% level of confidence were found.

## 4.2 Seasonal rainfall analysis

Figure 3 shows the mean monthly rainfall of selected stations to represent various regions of Sarawak namely, central-coast, south, north and interior region, respectively, based on their topography and geographical characteristics. There is a spatial and temporal variation in the monthly rainfall time series of Sarawak. The north and the interior regions experience unimodal mean monthly rainfall pattern due to the influence of the ITCZ and mountainous characteristic, while



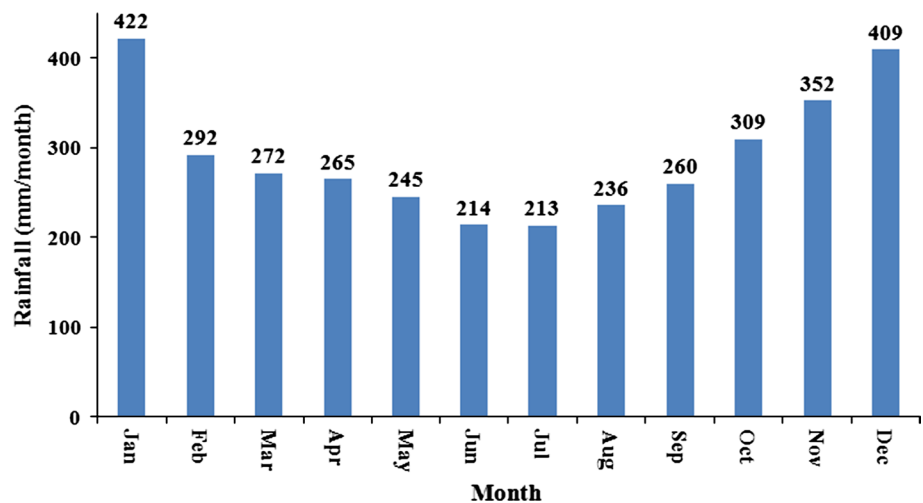
**Fig. 3** The mean monthly rainfall pattern at different stations in **a** central-coastal; **b** south; **c** north; and **d** interior regions of Sarawak. The numbers in the legend represent station number given in Table 1

the central-coast and the south regions experience single peak rainfall during NE monsoon. On average, the northern region of Sarawak receives the lowest amount of monthly rainfall at 244 mm while the interior region is the highest at 368 mm. Average rainfall for each region is shown in Fig. 3. A clear pattern of the monsoon influence on the distribution of the monthly rainfall can be seen in the central-coastal and south region which shows that rainfall was the lowest for May–September and the highest for November–March. The mean monthly rainfalls for all stations are shown in Fig. 4,

showing the monsoon pattern. Overall, Sarawak receives the highest amount of rainfall during the NE monsoon, which shares 49.5% of total annual rainfall compared to 33.9% during the SW monsoon. Meanwhile, during the Int-Aprl and Int-Oct, the winds are generally light and variable which contributes to 7.8 and 8.9% of the total mean annual rainfall, respectively.

Understanding the NE monsoon rainfall trend is important as it bring an exceptional heavy rainfall and frequently leading to the occurrence of floods. The most disastrous

**Fig. 4** Average of the monthly rainfall in Sarawak for the period of 1984–2014



floods in Sarawak were usually recorded in January and February during the NE monsoon. The spatial distribution of seasonal rainfall trends is shown in Fig. 5. The numbers of stations that experienced significant change in annual, seasonal and monthly rainfall at 90 and 95% significant levels are given in Table 2. Analysis of the monsoon rainfall of the MK test showed a significant level of increasing rainfall trend, and totaling at eight stations during NE monsoon and no decreasing station at 90% significance level as shown in Fig. 5a. Out of eight stations, the significant increase at 95% level of confidence was found at five stations. Rainfall was found to increase notably in the central-coastal and northern regions which have a direct impact from the NE monsoon facing toward it. However, the m-MK test showed no significant trend of rainfall during the NE monsoon at any stations.

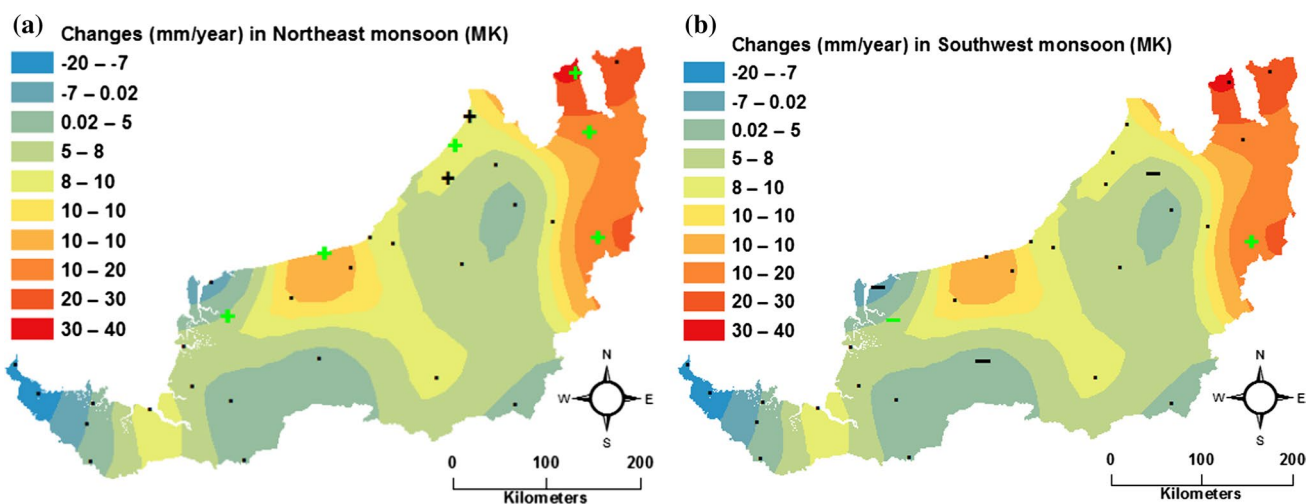
Rainfall trends by the MK test during the SW monsoon showed a 90% significance level of increasing rainfall trend at one station and decreasing at 4 stations (Fig. 5b). Meanwhile m-MK test showed no significant trend in any of the stations. The seasonal trend of the monsoon season by MK test indicates that there will be an increasing rate of rainfall during the NE monsoon, whereas the SW monsoon will become drier. As discussed by Sang et al. (2015) and the results from MK test indicates that the significant changes and worsening of the dry spells and extreme rainfall happening at the same time during both of the monsoon seasons but affecting the various region of Sarawak differently. However, the m-MK test revealed no significant trend in both NE and SW monsoon rainfall in Sarawak.

A significant trend in rainfall for all the months at all the stations is shown in Fig. 6. The results showed that the MK test detected the increase in rainfall trend in the 95% significance level was concentrated during the NE monsoon

months in most of the stations and decrease in March, April and November. On the other hand, the m-MK test showed no significant change in rainfall in any month of a year at any of the stations. Therefore, by applying m-MK test, it is possible to avoid overestimation of the climate changes impact on the significance of the rainfall trend in Sarawak.

### 4.3 Hourly rainfall analysis

Trends in six indices related to extreme rainfall events namely, maximum 1-, 3-, 6-, 12-, 24- and 72-h rainfalls in a year were assessed in this study. Figure 7 shows the spatial variation of trends in 1-, 3-, 6-, 12-, 24- and 72-h rainfalls detected by MK and m-MK trend tests. The numbers of stations showing any significant changes of six extreme rainfalls detected by MK and m-MK tests are presented in Table 3. The MK test showed changes in 1-, 3-, 6-, 12-, 24- and 72-h annual maximum rainfalls at 8, 5, 6, 6, 4 and 6 stations, respectively, out of 31 stations at the 90% level of significance level. On the other hand, the m-MK test showed significant changes in only one station for 6-, 12- and 72-h annual maximum rainfalls at the 90% level of confidence. At the 95% significance level, the MK test showed changes in 1-, 3-, 6-, 12-, 24- and 72-h annual maximum rainfalls at 7, 4, 4, 5, 3 and 5 stations, respectively, out of 31 stations while the m-MK test showed no trend at the 95% level of confidence at any station. The difference in trends in rainfall extreme indices from MK and m-MK indicates that most of the significant changes in annual maximum rainfall estimated by well-known MK test resulted from the scaling effect. It should be noted that the significant increasing trends in 1-h maximum rainfall by the MK test is detected mainly at stations located in the urban area of the towns

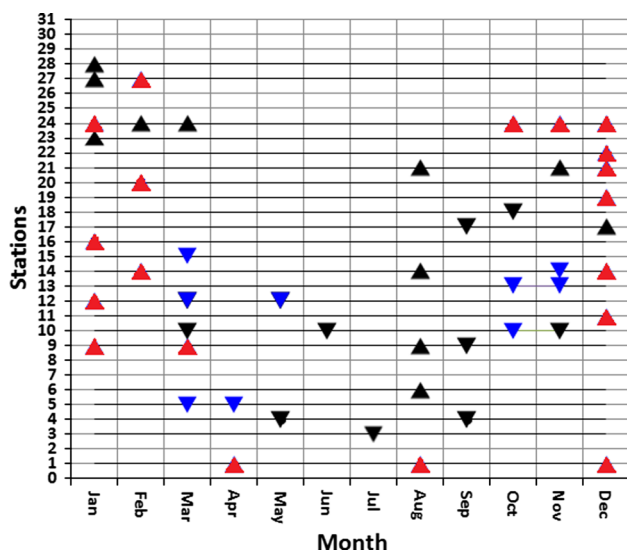


**Fig. 5** Spatial distribution in trend obtained using MK test and the rate of change of rainfall (mm/year) during **a** NE monsoon; and **b** SW monsoon over Sarawak in mm/year where (+) and (-) denotes

increasing and decreasing rainfall. The black sign represents 90% and the green sign represents 95% confidence level in the trend

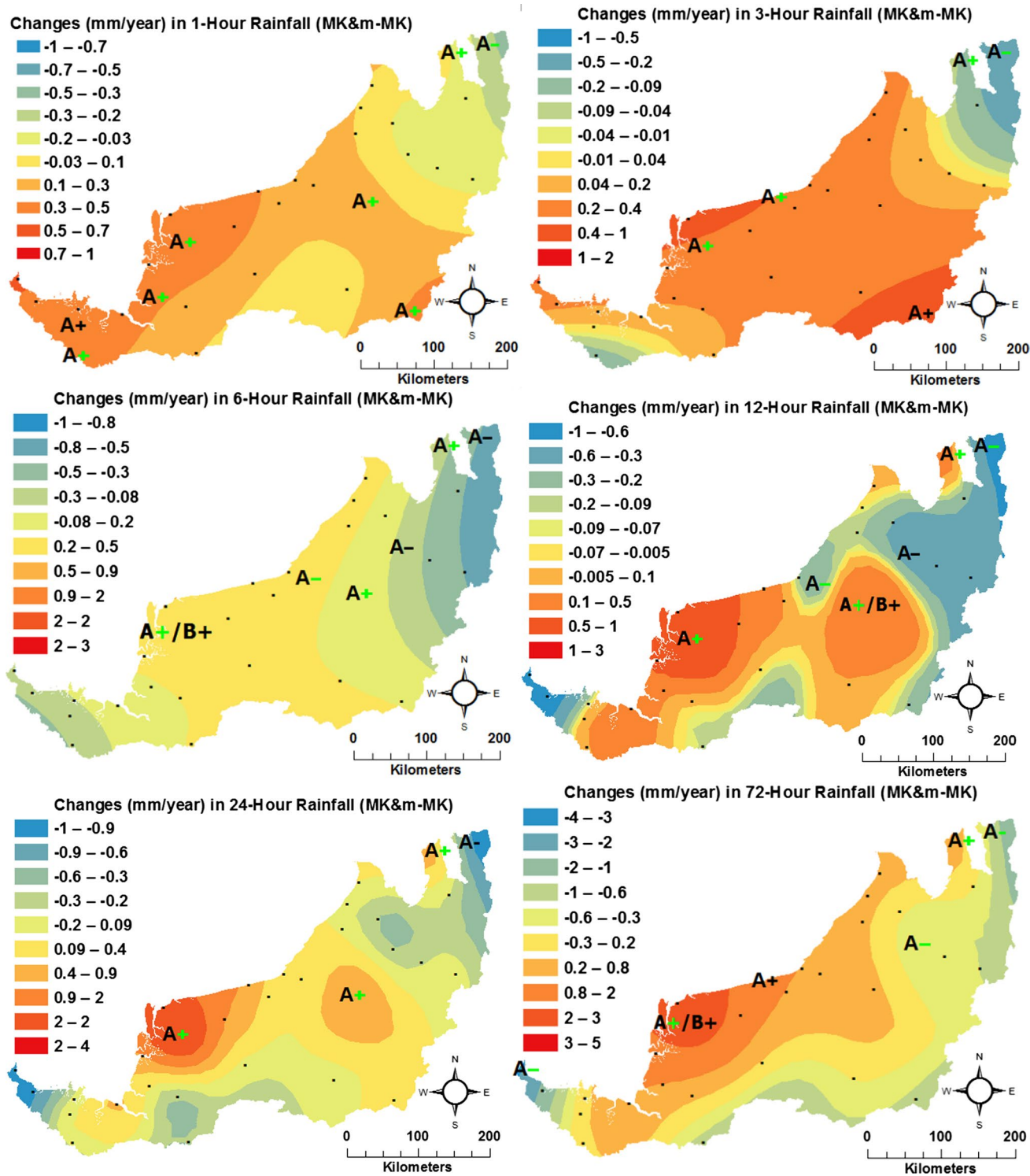
**Table 2** Numbers of stations showing any changes in annual, seasonal and monthly rainfall at 90 and 95% level of confidence

	90% sig. level						95% sig. level					
	MK			m-MK			MK			m-MK		
	Total	+	-	Total	+	-	Total	+	-	Total	+	-
Annual												
Jan–Dec	7	4	3	1	1	0	5	4	1	1	1	0
NE monsoon months												
Nov	5	2	3	0	0	0	3	1	2	0	0	0
Dec	8	8	0	0	0	0	7	7	0	0	0	0
Jan	7	7	0	0	0	0	4	4	0	0	0	0
Feb	4	4	0	0	0	0	3	3	0	0	0	0
Mar	6	2	4	0	0	0	4	1	3	0	0	0
NE monsoon												
Nov–Mar	8	8	0	0	0	0	6	6	0	0	0	0
Int. Monsoon												
Apr	3	1	2	0	0	0	2	0	2	0	0	0
SW monsoon months												
May	2	0	2	0	0	0	1	0	1	0	0	0
Jun	1	0	1	0	0	0	0	0	0	0	0	0
Jul	1	0	1	0	0	0	0	0	0	0	0	0
Aug	5	5	0	0	0	0	1	1	0	0	0	0
Sept	3	0	3	0	0	0	0	0	0	0	0	0
SW monsoon												
May–Sept	5	1	4	0	0	0	2	1	1	0	0	0
Int. monsoon												
Oct	3	1	2	0	0	0	1	1	0	0	0	0
All months total												
Jan–Dec	46	30	16	0	0	0	26	18	8	0	0	0

**Fig. 6** Trends in rainfall of different months detected by MK test at 90% significant level for 31 stations. Black (up-pointing triangle, down-pointing triangle) marker denotes significant positive and negative trends at 90% significant level. Meanwhile, red (up-pointing triangle) and blue (down-pointing triangle) marker denotes significant positive and negative trends, respectively, at 95% significant level

of Limbang, Bintulu, Saratok and Kuching which may potentially lead to the occurrence of the flash flood. Such information is crucial for city planner for overseeing the construction of the drainage and water management system. However, the m-MK test revealed no significant trend in annual maximum rainfall at urban stations. All the trends in annual maximum rainfall estimated by MK test are due to non-consideration of LTP.

The spatial distributions of the stations with significant level of increasing rainfall for annual maximum of 1-, 3- and 24-h rainfalls were irregularly distributed all over Sarawak for MK trend test with only one decreasing station at the north. It was notable that the significant trend of m-MK test at the 90% significance level was observed in the Lower Rajang basin in 6- and 72-h maximum rainfall, an area which was extensively being exploited for plantation such as oil palm, rubber and sago. These peat cultivation areas were prone to subsidence and with significant pro-long rainfall particularly during the NE monsoon, could lead to the worsening of the stagnant flood which happen regularly in the region. Irregularity of the significant increasing trend was observed in 6-, 12- and 72-h maximum rainfall by m-MK



**Fig. 7** Spatial distribution in trend and the rate of change (mm/year) in maximum 1-, 3-, 6-, 12-, 24- and 72-h rainfalls over Sarawak detected where A and B denotes for MK and m-MK test, respectively.

The symbols + and – denotes increasing and decreasing rainfall at 90% (black) and 95% (green) confidence levels

**Table 3** Numbers of stations showing any significant changes in maximum 1-, 3-, 6-, 12-, 24- and 72-h rainfalls at 90% significance level

Index (h)	MK					m-MK				
	Total	+	Urban (st no.)	-	Urban (st no.)	Total	+	Urban (st no.)	-	Urban (st no.)
1	8	7	24, 29, 30	1	9	0	0	-	0	-
3	5	4	24, 27	1	9	0	0	-	0	-
6	6	3	24	3	3, 8, 9	1	1	-	0	-
12	6	3	24	3	3, 8, 9	1	1	-	0	-
24	4	3	24	1	9	0	0	-	0	-
72	6	3	27	3	3, 6, 9	1	1	-	0	-

24 = Limbang town, 27 = Bintulu town, 29 = Saratok town, 30 = Kuching town

St no. station number as in Table 1

test, implying the role of the local topography and location in dictating the climate variability of the region.

## 5 Discussion and conclusion

The trends in annual, seasonal and monthly rainfalls and rainfall extremes at 31 stations of Sarawak for the period 1980–2014 have been assessed in this study using MK and m-MK tests. Obtained results show that significant trend in annual and seasonal rainfall and rainfall extremes estimated by the MK test is rejected by the m-MK test in most stations. The present study indicates no significant trend in seasonal and monthly rainfall at any stations of Sarawak. The significant change in annual and some rainfall extremes were detected at only one or two stations by the m-MK test. The results indicate that changes in annual, seasonal and monthly rainfalls and rainfall extremes in Sarawak are not significant. The trends detected by the MK test are due to LTP phenomena.

The climate of Sarawak is highly influenced by large-scale atmospheric phenomena and in situ synoptic systems (Tangang et al. 2008). Robertson et al. (2011) reported that rainfall in the region is heavily influenced by the MJO and cold surges (CS), which can interact with each other as well as with in situ synoptic systems such as the Borneo vortex, often leading to torrential rainfall, flash floods, and severe storms. In general, CS is significantly more likely to trigger extreme rainfall. However, the largest extreme rainfall events are obtained when both CS and MJO occur (Lim et al. 2017). It has been reported that the increase in global temperature caused MJO stronger and more frequent (Chang et al. 2015). The warming effect in Siberia has also led to increase in the frequency of CS. Lim et al. (2017) reported an increase in the frequency of the CS events between 1980–2001 and 1998–2012 in Southeast Asia. The increase in frequency of CS and MJO may have caused increased the extreme rainfall events in the region. The present study revealed that

the impact of increasing frequency of CS and MJO is still invisible in the study area.

The MK trend test assumes independent or only short-range persistent data (Hamed 2008). However, a large number of recent studies reported that hydro-climatic records are characterized by LTP where the corresponding autocorrelation function decays algebraically (Franzke 2012; Bunde et al. 2014; Markonis and Koutsoyiannis 2015; Ludescher et al. 2016; Iliopoulou et al. 2016; Tyralis et al. 2017). The studies suggested that the estimates of trend significance are highly sensitive to LTP assumptions. The LTP processes can create an apparent trend which last for rather long periods than the short-range persistent processes and thus, directly affects the significance of trends. Therefore, investigation of trends based on assumption of independence or short-term persistence may lead to an overestimation of the significance of trend. The studies revealed that number of stations showing significant trends using MK test reduces drastically when m-MK test is adopted (Kumar et al. 2009; Shahid et al. 2014; Fathian et al. 2015). The studies suggest that consideration of LTP in hydrologic time series is very important for reliable trend investigation.

Lacombe et al. (2012) assessed the long-term trend in precipitation over Southeast Asia using m-MK test and found a significant trend only at a few locations. They argued most of the previous findings of significant precipitation changes over Southeast Asia resulted from were due to mixing up multi-decadal variability and long-term unidirectional trends. Rao et al. (2011) evaluated the trends in Malaysian monthly runoff under the scaling hypothesis and reported no statistically significant trends which also contradict with the results obtained using the MK test. In Bangladesh, Shahid et al. (2014) reported that significant trends obtained in rainfall amount and extremes at many stations by previous studies were due to LTP. After removing the scaling effect, they found that the rainfall is increasing only in northern Bangladesh and in pre-monsoon season. Kumar et al. (2009) studied the streamflow trends in Indiana considering the

effects of LTP and reported that the number of stations that show trends in low and medium flow statistics decreases up to 70% when LTP is considered in the analysis. Some other studies also reported that the station number having significant trends from MK test were reduced when LTP was taken into consideration. (Ehsanzadeh and Adamowski 2010; Fathian et al. 2015). The difference in the numbers of significant trends in annual, seasonal and monthly rainfalls and rainfall extremes are also obtained in this study using MK and m-MK. The difference between MK and m-MK test also indicates the importance of using m-MK test to avoid overestimation in rainfall trend.

Assessment of the changes in precipitation characteristics is very important for Sarawak, Malaysia which is one of the most biologically diverse regions of the world where small changes in rainfall characteristics can critically affect the health of the forest and the ecological systems. The rainforest of Sarawak has one of the highest concentrations of species per unit area in the world. Because of the high species diversity, species of tropical rainforests have narrow niches (Forest Department Sarawak 2013). Changes in rainfall may significantly affect microenvironment of species and reduce biological diversity (Rashid et al. 2015). Furthermore, rainfall plays an important role in the yield of oil palm, which is one of the major drivers of economies of Sarawak. High rainfall causes poor pollination and less photosynthesis, and consequently, reduces the yield of oil palm (Harun et al. 2014). Therefore, increasing trend in rainfall and rainfall extremes may severely affect oil palm based economy in the region.

This study provides an elaborate view of recent trends in rainfall of Sarawak. The incorporation of LTP has provided better information regarding the significance in precipitation trends. It is expected that these results will encourage researcher to conduct similar study in other regions in the world to re-evaluate the trends in annual, seasonal, and monthly rainfalls and rainfall extremes using different trend analysis methods.

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