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Variability of rainfall in Peninsular Malaysia

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Abstract

This study analyzed and quantified the spatial patterns and time-variability of rainfall in Peninsular Malaysia on monthly, yearly and monsoon temporal scales. We first obtained an overview of rainfall patterns through the analysis of 16 point data sources. The results led to choosing three distinct regions, i.e. the east coast, inland and west coast regions. For detailed analysis, Shepard's interpolation scheme was applied to the station data to produce daily rainfall fields on a 0.05 degree resolution grids for the period 1971–2006. The rainfall characteristics in time and space derived from a frequency analysis were found to be distinctly different in these three regions. In the east coast region, monthly rainfall shows a significant periodicity dominated by an annual cycle, followed by a half-year cycle. The inland and west coast regions show that the dominant periodic fluctuations in the monthly rainfall are dominated by a half-year cycle, followed by an annual cycle. The long-term rainfall variability analysis shows that the dry and wet conditions in Peninsular Malaysia are not primarily governed by the ENSO events. The results from the individual regions suggest that although the relative variability is influenced by ENSO, local and regional conditions have an effect on the interannual rainfall variability, which is superimposed on the large-scale weather conditions. A significant increasing trends in annual rainfall (9.3 mm/year) and northeast monsoon rainfall (6.2 mm/monsoon) were only detected in the west coast region. No trend was found in the monthly rainfall, except for November in the west coast region. The spatial variation analysis shows that the east coast region, which received substantially higher amounts of rainfall during the northeast monsoon, has lower spatial rainfall variability and a more uniform rainfall distribution than other regions. A larger range for the monthly spatial variation was observed in the west coast region.

1 Introduction

Understanding the spatial and temporal of rainfall variability is important element in gaining knowledge of water balance dynamics on various scales for water resources management and planning. Peninsular Malaysia lacks of detailed quantitative studies partly because of the limited number of stations with long records and the problem of missing data (Moten, 1993). Most studies were conducted in the 1980s and 1990s. An agroclimatic study by Nieuwolt (1982), introduced a simple method to quantify rainfall variability over time and related the results to agriculture. The temporal and spatial characteristics of rainfall have been investigated, but often restricted to a small catchments, e.g. an urbanized area (Desa and Niemczynowicz, 1996) and a forested catchment (Noguchi and Nik, 1996). Desa and Niemczynowics (1996) emphasized the need of having rainfall data with better accuracy and time resolution. Annual rainfall maps are derived from the data of monthly long-term records (1950–1990) by the Economic Planning Unit (1999). These maps are only able to show us the spatial distribution of rainfall in the country instead of variable rainfall patterns over time.

Some efforts have also been made during the 2000s to study the formation and occurrence of rainfall and extreme rainfall events in the region. For example, the synoptic-scale disturbances over the South China Sea vicinity were investigated by Chang et al. (2005), and the relation between Malaysian rainfall anomalies, sea surface temperature and El Nino-Southern Oscillation were studied by Tangang and Juneng (2004) and Juneng and Tangang (2005, 2007) However, the rainfall trends and distributions received less attention. Furthermore, the growing concern about climate change emphasized the need for detailed information about the space and time distribution of rainfall.

To compensate the gap, the Regional Hydroclimate Model of Peninsular Malaysia (RegHCM-PM) has been developed at a spatial resolution of 9 km to assess the impact of future climate change, and the hydrology and water resources of Peninsular Malaysia (NAHRIM, 2006). However, the model simulated only ten years (1984–1993) of historical hydroclimatic data from 18 stations in order to assess the potential changes in atmospheric and hydrological conditions over the region. Analysis of the spatial and temporal of rainfall patterns analysis was not considered.

The aim of this paper is to analyze the patterns and variability of rainfall in Peninsular Malaysia. To this study, a large number of observation records with good spatial distribution from a period of 35 years until 2006 have been interpolated into a daily gridded data set. Section 2 describes the study area and the available observation data. Section 3 covers the adopted methods for the interpolation and the analysis methods. The results of the analyses are presented and discussed in Sect. 4. Section 5 summarizes some key points and presents the conclusions from the study.

2 Study area and data

2.1 Description of the study area

Peninsular Malaysia is located between 1° and 7° north and 99° to 105° east, and comprises an area of 131 587 km^2. It is composed of highland, floodplain and coastal zones. The Titiwangsa mountain range forms the backbone of the Peninsula, from southern Thailand running approximately south-southeast over a distance of 480 km and separating the eastern part from the western part (Suhaila and Jemain, 2007). Surrounding the central high regions are the coastal lowlands. The weather of Peninsular Malaysia is warm and humid all year round with temperatures ranging from 21°C to 32°C, as is characteristic for a humid tropical climate. The precipitation climate is characterized by two rainy seasons associated with the Southwest Monsoon (SWM) from May to September and the Northeast Monsoon (NEM) from November to March (Camerlengo and Demmler, 1997; Tangang, 2001; Suhaila and Jemain, 2009). Substantial rainfall also occurs in the transitional periods (usually occur in April and October) between the monsoon seasons (Suhaila and Jemain, 2007) .

2.2 Data sources

The daily rainfall data used in this study originates from three data sources, i.e. the automatic station database of the Department of Irrigation and Drainage (DID), the Malaysia Meteorological Department (MMD), the Global Summary of the Day (GSOD/WMO-GTS) (retrieved from NOAA/NCDC), and additional GEWEX Asian Monsoon Experiment (GAME) data which also originate from MMD. Figure 1 shows the distribution of the stations that were selected from this study after quality control. Rainfall amounts are collected over 24 h periods beginning 08:00 at Malaysian time which equals 00:00 UTC.

Figure 2 presents the number of available daily observations from the individual data sources and their combination for the period 1971 to 2006. There are limited daily observations available before 1973. The total number of observations is relatively stable after 1975, except for the lack of GSOD/WMO-GTS observations during short periods. The combination of the three data sets has an average of 123 daily observations with maxima of 167 for 2001 and 2003.

3 Methodology

3.1 Rainfall data interpolation

The available rainfall data have been interpolated into daily grids with 0.05 degree resolution (approximately 5.5 km). The interpolation scheme is based on an adaption of Shepard's (1968) angular distance weighting (ADW) procedure, which was found to perform better than the triangulation and Thiessen polygon methods in areas with sparse data (New et al., 2000). It is assumed that beyond a certain distance, the spatial correlation between point observations becomes insignificant (Dai et al., 1997; New et al., 2000; Caesar et al., 2006). A decay function for the correlation can be defined as

$$r = r_0 \exp(-\frac{x}{x_0}) \tag{1}$$

where with $r_0=1$, x_0 is the correlation decay distance (CDD) for which r falls to $1/e$ and x is the distance from the point of interest. A distance weight at any grid point for any station k is obtained from the power relation

$$w_k = r^m \tag{2}$$

in which higher values of the parameter m cause a steeper decay of the weight. The value for m generally varies from 1 to 8 (Dai et al., 1997). The angle weights for $n_j$selected stations are given by

$$a_k = \frac{\sum_{l=1}^{n_j} w_l [1 - \cos\theta_j(k,l)]}{\sum_{l=1}^{n_j} w_l}, \quad l \neq k \tag{3}$$

where $\theta_j(k,l)$ is the angle between the vertices from data points k and l, and the grid point j. The final angular-distance weight is obtained from the combination

$$W_k = w_k(1 + a_k) \tag{4}$$

The interpolated value at grid point j is then obtained from the $n_j$observation values P through

$$\hat{P}_j = \frac{\sum_{k=1}^{n_j} W_k P_k}{\sum_{k=1}^{n_j} W_k} \tag{5}$$

The implementation of the algorithm uses a value of $n_j=10$ stations nearest to the grid point of interest. The power coefficient is set to $m=4$.

3.2 Selection of characteristic regions

In a preliminary analysis, sixteen representative stations with long data records that are well distributed across Peninsular Malaysia were selected. Figure 3 shows the mean monthly rainfall recorded at these stations.

Three regions can be distinguished from the rainfall distribution of selected stations, as pointed out previously by Dale (1960) and Nieuwolt (1968). The east coast, inland and west coast regions are characterized by a distinct monthly rainfall distribution pattern. The east coast has a pronounced maximum at the end of the year. The west coast has a semi-annual pattern with two maxima during the monsoon periods. The inland region is similar to the west coast region, but the mean annual rainfall amount is relatively lower. The southern and northern regions do not show a clear rainfall pattern changes. According to Nieuwolt (1968), the southern region has its own diurnal rainfall regime that does not correspond to any of the three other regions. Therefore, three regions were selected for regional analysis, which are shown in Fig. 4.

For the present study, three analysis steps were carried out. First, a harmonic analysis was used to test the relative importance of periodic variations. Second, trends were investigated using Spearman's rank test. Finally, the spatial variability of monthly and annual rainfall was investigated.

3.3 Harmonic analysis

Harmonic analysis, is often applied to streamflow (Quimpo and Yang, 1970; Chiew and McMahon, 2002) and groundwater (Zhou, 1996; Kim et al., 2007) time series. It has also been used for areal and temporal analysis of rainfall (Scott and Shulman, 1979), and studies of seasonal variation of rainfall (Kirkyla and Hameed, 1989) and rainfall climatology (Kadioglu et al., 1999; Vines, 2007). Periodic characteristics of rainfall time series can be modelled by a harmonic series (Bloomfield, 1976), i.e.

$$h_t = A_0 + \sum_{j=1}^{k} \left[A_j \cos(2\pi f_j t) + B_j \sin(2\pi f_j t) \right] + \varepsilon_t \tag{6}$$

where A_0 is the mean of h_t, $A_j$and B_j are the fourier series coefficients, j is the j-th harmonic, k is the total number of harmonics, t is the time, f_j is the frequency of the j-th harmonic and ε_t is the t-th residual. A detailed explanation of method is presented in Appendix A.

Only a few harmonics are necessary for a good fit of periodic components to small-interval hydrological time series (Quimpo and Yang, 1970; Hall and O'Connell, 1972; Salas et al., 1985). The method for selecting the significant harmonics that fit to a periodic series is based on the cumulative periodogram, as described in Appendix A.

3.4 Spearman's rank test

The rank-based non-parametric Spearman's rank or Spearman's rho statistical test (Dahmen and Hall, 1990; Sneyer, 1990) is used to assess the existence of trends in the rainfall time series. The hypothesis is tested that there is no correlation between the order in which the data are observed and the increase or decrease in magnitude of those data. The method is described further in Appendix B. A confidence interval of 95% is used for evaluating presence or absence of trends. It is noted that at a significant level of 5% (two-tailed), the significance of the test statistic t values vary with the number of observations and selected confidence interval.

3.5 Spatial variation

Assessment of spatial variation is based on computation of the spatial variance within a particular gridded region, as

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2 \quad (7)$$

where $\overline{x}$ is the average areal rainfall and, x_i is the rainfall depth in each grid cell. The average areal rainfall and the spatial variance are computed for each region. The square root of spatial variance in Eq. (7) yields the standard deviation of the spatial rainfall in the selected region. The coefficient of variation of rainfall, is defined as the standard deviation divided by the average areal rainfall, was used to characterize the monthly and annual spatial variability of rainfall.

4 Results and discussions

4.1 Mean monthly rainfall in Peninsular Malaysia

The mean monthly areal rainfall data for entire Peninsular Malaysia are presented in Fig. 5. The result agrees with the findings by Moten (1993). Maximum rainfall is observed near the end of the year during the NEM. A secondary maximum is found during the intermonsoon months (April or May). The highest mean monthly rainfall of 314 mm is observed in December, equivalent to 14% of the mean annual rainfall. The lowest mean monthly rainfall of 115 mm occurs in February, which contributes about 5% to the mean annual rainfall. It is noted that during the NEM from November to March both the maximum and minimum monthly rainfall are observed. A relative high rainfall variation is observed during the NEM than the SWM, which occurs from May to September.

4.2 Harmonic analysis

The results of the harmonic analysis for monthly rainfall gridded time series are shown in Table 1. It is noted that two peaks repeat every year in the east coast region as shown in Fig. 6a. The dominant periodic fluctuation is the annual cycle and the secondary important fluctuation is at a half-year period. However, the opposite is true for the inland and west coast region as shown in Fig. 6b and c, respectively, where dominant cycle occurs at a half-year frequency, followed by the annual fluctuation. The harmonic analysis of the yearly and monsoon time series for all regions did not reveal any significant periodic multiple-year changes.

The rainfall in the east coast region of Peninsular Malaysia is mostly influenced by the NEM, particulary during November or December (the dominant month in the annual fluctuation as shown in Fig. 6a). The secondary half-year period cycle is mostly influence by the SWM in May or June. For the west coast region, April and October are predominant in the annual rainfall contribution, coincide with the intermonsoon periods. The inland region is less influenced by the intermonsoon period. The rainfall in May is contributing most of the annual rainfall, followed by November. It is noted that May and November are the beginning of the SWM and NEM, respectively. Thus, the monsoon conditions have a different effect on the rainfall distribution in the three regions. In general, starting in November, the rainfall maxima shift from east to west during a year.

The monsoon contributions to the annual rainfall in each region are shown in Table 2. The east coast region received 3124 mm of mean annual rainfall, 55% and 31% of which occured during the NEM and SWM periods, respectively. The monsoons contribute 86% of the total annual rainfall in this region. During the NEM, the dry northeasterly wind becomes moist during the passage over the South China Sea. The interaction between with the land along the east coast area creates deep convection clouds and rainfall (Chang et al., 2005). The high rainfall in the east coast has also been explained from the low outgoing longwave radiation (OLR) over Peninsular Malaysia before and after the winter monsoon in the Northern Hemisphere (Murakami, 1980).

During early winter (November–December), the OLR values are relatively low over the South China Sea, where equatorial disturbances frequently develop. During late winter (January–February), the disturbance activity becomes less pronounced, which is reflected by a relatively high OLR over the South China Sea (Murakami, 1980). Other disturbances, such as the formation of the Borneo vortex and Madden Julian Oscillation are also believed to enhance low-level moisture convergence and organize deep convective rainfall (Cheang, 1977; Chang et al., 2005; Tangang et al., 2008) along the east coast. According to Ramage (1964), during the SWM, the strengthening of afternoon sea breezes in opposite direction of the land winds deepens clouds and forces the convergence clouds to drift landward, producing high downpour in the coastal zone in the late afternoon.

The inland region received a relatively smaller amount of mean annual rainfall, 2079 mm, 80% of which occurred during the NEM and SWM. The reduction of rainfall amount in the inland during NEM is due to Titiwangsa mountain range (see Fig. 3) that appears to block the westward progression of the climatic system and therefore inhibits excessive rainfall over the inland areas (Juneng et al., 2007). The rainfall produced in this region is mainly due to local convection caused by intense heating of the land surface (Nieuwolt, 1968).

For the west coast region, the monsoon rainfalls contribute 78% to the mean annual rainfall of 2311 mm (see Table 2). Although the west coast region experiences relatively high rainfall during the SWM, the influence of the NEM is still larger by some 4% of the mean annual total. This is attributed to several reasons by Nieuwolt (1968). The SWM has generally lower wind speeds than the NEM. Most winds during SWM come to Peninsular Malaysia from Sumatra, where the high mountain ranges create rain sheltering effects for the west coast of Peninsular Malaysia. As the Strait of Malacca becomes wider towards the north, the land-sea breeze and convection become the more important and may cause regional and local differences in rainfall patterns (Oki and Musiake, 1994; Jamil et al., 2009).

The mean annual rainfall in the entire Peninsular Malaysia was approximately

2300mm. A total 81% of the mean annual rainfall is originated from monsoon rainfall. The large amount of NEM rainfall clearly stands out from Peninsular Malaysia as a whole.

4.3 Long-term variability

Figure 7 shows the relation between the annual standardized rainfall index (SPI) and the El Niño Southern Oscillation (ENSO) periods for Peninsular Malaysia and the three regions in this study. The SPI is obtained as the difference between annual and mean annual rainfall, normalized by the standard deviation of the annual rainfall for the period (Mckee et al., 1993). The indication of El Niño and La Niña periods has been adopted from MMD (2009) and is based on the southern oscillation index, which is obtained from the difference in surface pressure at Tahiti and Darwin (Nicholls and Wong, 1990). El Niño episodes are generally associated with warm and dry conditions, and the opposite holds for La Niña episodes.

For Peninsular Malaysia as a whole (see Fig. 7), the relatively wet years of 1987, 1988 and 1994 are not associated with La Niña episodes. The dry period from 1976 to 1983 is not fully explained by El Niño episodes. Similarly, the relatively wet periods 1993–1995 and 1999–2001 are not fully explained by La Niña episodes.

Relatively wet years in the east coast region of 1986, 1991 and 1994 are not associated with La Niña episodes, and the dry year 1998 is not fully related to El Niño. For both the inland and west coast regions, the wet years in 1986–1987 and 1994 are not associated to El Niña. Similarly, dry year is reported in 1999 during the La Niña episode in both regions.

The above analysis shows that the dry and wet conditions in Peninsular Malaysia are not primarily governed by the ENSO events, which confirms the MMD (2009) findings. The results from the individual regions suggest that although the relative variability is influenced by ENSO (cf. Nicholls and Wong, 1990), local and regional conditions have an effect on the interannual rainfall variability, which is superimposed on the large-scale weather conditions.

In the rainfall trend analysis, no significant trends at the 95% confidence level were found for mean annual and monsoon rainfalls in the east coast and inland region. In contrast, significant trends have been found in the mean annual, NEM and November rainfall for the west coast region. Figure 8a and b shows an increase of 9.3 mm/year and 6.2 mm/year for mean annual and mean NEM rainfall, respectively. The mean November rainfall as shown in Fig. 8c depicts an increasing trend of about 2.0 mm/year.

A significant trend found in the mean annual and mean NEM rainfall was probably due to the accumulation of increasing trend of other months though they are not significant at 95% confidence level.

4.4 Spatial variation of rainfall

Figure 9 compares the variations in mean monthly areal rainfall and the mean monthly fluctuations in spatial variability for the three regions. It is noted that the east coast region has the largest mean rainfall. However, the spatial rainfall variation is more uniform throughout the year. The inland and west coast regions receive smaller amount of monthly rainfall, but the spatial rainfall variation differs in particular during the monsoons. The larger range of the coefficient of variation is most visible in the NEM, and to a smaller extent in the SWM. Most of the spatial variability in the west coast region is observed during the NEM, which brings largest amount of rainfall to the east coast region. For the inland region, the largest spatial variability occurs in February, has the smallest rainfall in quantity.

The interquartile range (0.15) and mean (0.36) monthly coefficients of variation for the west coast region is relatively larger compared to the other regions. The east coast region has the smaller range and lowest mean coefficient of variation indicating a slightly more uniform of areal distribution of rainfall. The calculated median values of the coefficients of variation are close to the mean values for all regions, which suggests that the spatial rainfall variation is normally distributed.

The topography and monsoon winds are probably the main factors controlling the magnitude of the spatial rainfall variation in the country. The relatively flat landscape of the east coast region may result in reduced spatial variability of rainfall. The movement of storms through the regions due to the monsoon winds may have implications to the rainfall distributions as is explained in Sect. 4.2. A trend analysis of the long-term spatial rainfall variation did not show a significant trend for all three regions.

5 Conclusions

In this paper, we studied the rainfall patterns in space and time during 1971–2006 in Peninsular Malaysia. First, gauge data were used in a preliminary study to obtain a broad overview of the rainfall distribution. Subsequently, Shepard's interpolation scheme was applied to create a gridded daily data set at 0.05 degree resolution. Three distinct regions, namely east coast, inland and west coast were selected for analysis of long-term trends and spatial variability. The southern and northern regions were not included into this study, mainly due to a lack of significant monthly and yearly periodical changes in the harmonic analysis during the preliminary study. Some conclusions can be drawn as follows:

1. In the east coast region, the periodic change is dominated by an annual cycle and followed by a half-year cycle. There are no yearly and monsoon trends visible in the harmonic analysis results. The NEM and SWM contribute 55% and 31% of the total annual rainfall, respectively. T he rainfall characteristics of this region are mainly influenced by the NEM. The spatial variability of monthly rainfall was the lowest among the three regions. Although this region received higher amounts of monthly rainfall, the spatial distribution is more uniform. This is attributed to the relatively flat landscape in this region.
2. In the inland region, two rainfall maxima were observed in the monthly periodical changes. The periodic fluctuations were dominated by a half-year cycle, followed by an annual cycle. About 80% of total annual rainfall is contributed by the NEM

(43%) and SWM (37%). The largest spatial variability occurs in February, which is the month with the smallest amount of rainfall.

3. In the west coast region, the dominant periodic fluctuation occurs at half-year cycles, followed by an annual cycle. Significant rainfall trends with relatively small increases were found for November, the NEM and annual rainfall. The trends in mean annual and mean NEM rainfall are probably due to the accumulation of increasing trends in monthly rainfall, although these are not significant at 95% confidence level. The rainfall contributions from the SWM (37%) are relatively more important in this region. The NEM dominates in this region with 41% of the total rainfall. This region shows a relatively higher interquartile range and larger spatial rainfall variation in mean monthly rainfall. The larger range of the coefficient of variation is most visible during the NEM and SWM periods.

4. The long-term rainfall variability analysis shows that the dry and wet conditions in Peninsular Malaysia are not primarily governed by the ENSO events. Even though the rainfall variability of the individual regions is influenced by ENSO, local and regional conditions have an effect on the interannual rainfall variability, which is superimposed on the large-scale weather conditions.

5. There was no significant trend found in the rainfall spatial variability in the three distinct regions in Peninsular Malaysia.

Appendix A

Harmonic analysis

Harmonic analysis of a time series uses a Fourier series to analyze periodic fluctuations

$$h_t = A_0 + \sum_{j=1}^{k} \left[A_j \cos(2\pi f_j t) + B_j \sin(2\pi f_j t) \right] + \varepsilon_t \tag{A1}$$

where A_0 is the mean of h_t, $A_j$and B_j are the fourier series coefficients, j is the harmonic, and k is the total number of harmonics which can be equal to $n/2$ or $(n–1)/2$ depending on whether n is even or odd, respectively. n is the total number of observations and t is the time interval within specific time series. For instance, for monthly series is n=12 and k = 6, for weekly series with n=54, and k=26, and for daily series is n=365 and k=182. Bloomfield (1976) proved that $(A_j^2 + B_j^2)^{1/2}$ and $f_j = j/n$ are the amplitude and frequency for the j-th harmonic ε_t is the t-th residual.

Using the linear least squares method, the constant and the harmonic coefficients can be estimated as:

$$A_0 = \bar{h} = \frac{1}{n} \sum_{t=1}^{n} h_t \tag{A2}$$

$$A_j = \frac{2}{n} \sum_{t=1}^{n} h_t \cos(2\pi f_j t), \quad j = 1, 2, \ldots, n/2 \tag{A3}$$

$$B_j = \frac{2}{n} \sum_{t=1}^{n} h_t \sin(2\pi f_j t), \quad j = 1, 2, \ldots, n/2 \tag{A4}$$

when n is even the last coefficients A_k and B_k are

$$A_k = \frac{1}{n}\sum_{t=1}^{n}(-1)^t h_t \tag{A5}$$

$$B_k = 0 \tag{A6}$$

A graphical and likely the most often used method for selecting the significant harmonics which fit a periodic series, is the cumulative periodogram test (Salas et al., 1985) defined as:

$$CP_i = \frac{\sum\limits_{j=1}^{i}\mathrm{MSD}(j)}{\mathrm{MSD}(h)}, i = 1, 2, ..., k \tag{A7}$$

where MSD(h) is the mean squared deviation of h_t around $\bar{h}$ (equivalent to the definition of variance in statistical terms) and is determined by:

$$\mathrm{MSD}(h) = \frac{1}{n}\sum_{t=1}^{n}(h_t - \bar{h})^2 \tag{A8}$$

MSD(j) is the contribution of the j-th harmonic to the mean squared deviation and is determined by:

$$\mathrm{MSD}(j) = \frac{1}{2}(A_j^2 + B_j^2), j = 1, 2, ..., k \tag{A9}$$

MSD(j) is arranged in decreasing order.

The plot of CP$_i$ versus i is called the cumulative periodogram (Salas et al., 1985). A graphical criterium using the cumulative periodogram for obtaining the significant harmonics, is based on the concept that the variation of the CP$_i$ versus i. The plot is composed of the two distinct parts, i.e. (1) a periodic part of a fast increase of CP_i with i, and (2) a sampling part of a slow increase of CP_i with i. The point where these two parts intersect corresponds to the number of significant harmonics. In particular, for a white noise series, the cumulative periodogram would be a straight line.

Appendix B

Spearman's rank test

The Spearman coefficient of rank correlation R_{sp} (Dahmen and Hall, 1990; Sneyer, 1990) is defined as

$$R_{sp} = 1 - \frac{6\sum D_i^2}{n(n^2-1)} \tag{B1}$$

where $D_i = Kx_i - Ky_i$, when two or more observations, D_i, have the same value, the average rank Ky_i is calculated. A test-statistic t_t is used to test the null hypothesis $H_0{:}R_{sp}=0$ (there is no trend) against the alternative hypothesis $H_1{:}R_{sp}\neq 0$ (there is a trend). The test statistic is defined as

$$t_t = R_{sp}\left(\frac{n-2}{1-R_{sp}^2}\right)^{\frac{1}{2}} \tag{B2}$$

The test statistic t_t has Student's t-distribution with $v=n-2$ degrees of freedom, where n is the number of elements in a sample. The hypothesis H_0 is accepted when the computed t_t is not contained in the critical region. In other words, one concludes there is no trend when

$$t(v, 2.5\%) < t_t < t(v, 97.5\%) \tag{B3}$$

If the computed t_t value lies within the desired confidence limits, we can conclude that there is a trend in the series.

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Table 1. Results of periodic changes of monthly gridded rainfall time series for three distinct regions in Peninsular Malaysia.

Region	Parameters of harmonics					
	j	T_j	MSD(j)	CP$_j$	A_j	B_j
East Coast	1	12	13654.35	0.28	148.10	−73.32
	2	6	7260.22	0.43	102.14	−63.93
Inland	1	6	1242.76	0.22	9.91	−48.86
	2	12	767.86	0.36	30.41	−24.72
West Coast	1	6	1992.44	0.34	−11.00	−62.16
	2	12	549.31	0.43	22.45	−24.38

Note: j is the j-th harmonic; T_j is the period (month) of the j-th harmonic; MSD(j) is the mean squared deviation of the j-th harmonic; CP$_j$ is the cumulative periodogram; A_j and B_j are the j-th harmonic coefficients.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 2. Monsoons rainfall contributions in Peninsular Malaysia.

Region	Annual Rainfall (mm)	NEM (Nov-Mar) Rainfall		SWM (May-Sep) Rainfall		Total Monsoons Rainfall	
		mm	%	mm	%	mm	%
East Coast	3124	1717	55	978	31	2696	86
Inland	2079	885	43	774	37	1659	80
West coast	2311	937	41	866	37	1803	78
Peninsular Malaysia	2334	1034	44	861	37	1894	81

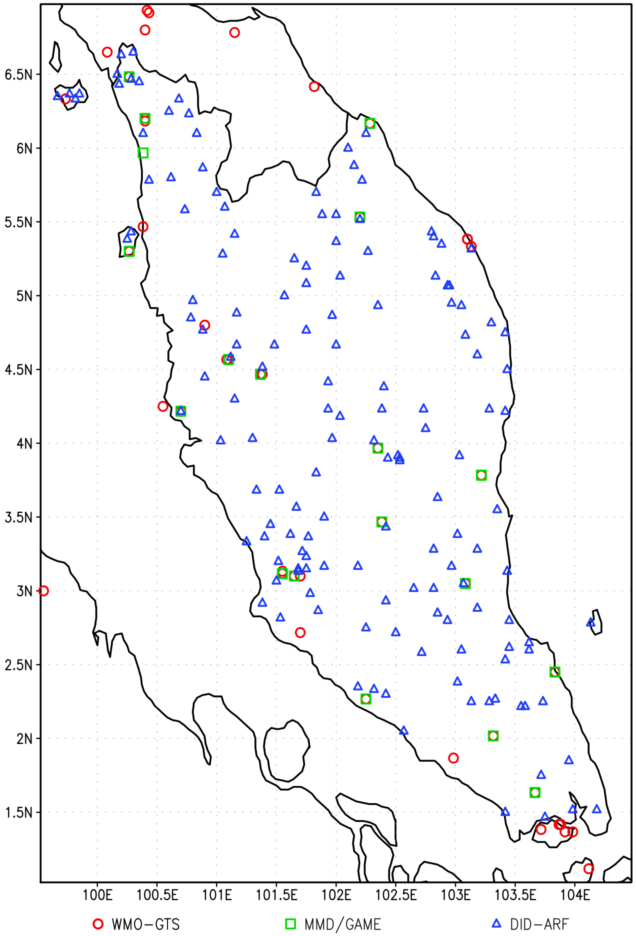

Fig. 1. Location of the stations included in the study.

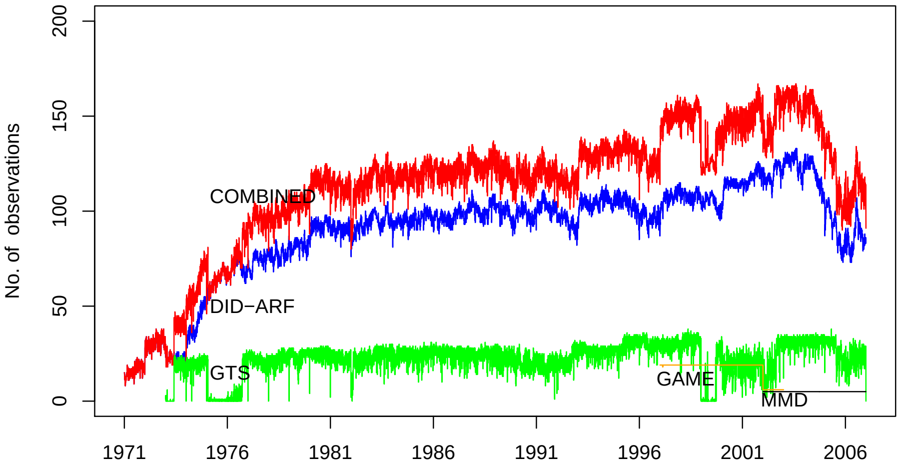

Fig. 2. Number of observation daily rainfall over the analysis domain collected from the MMD (black), GAME (orange), WMO-GTS (green), DID-ARF (blue) and their combination (red).

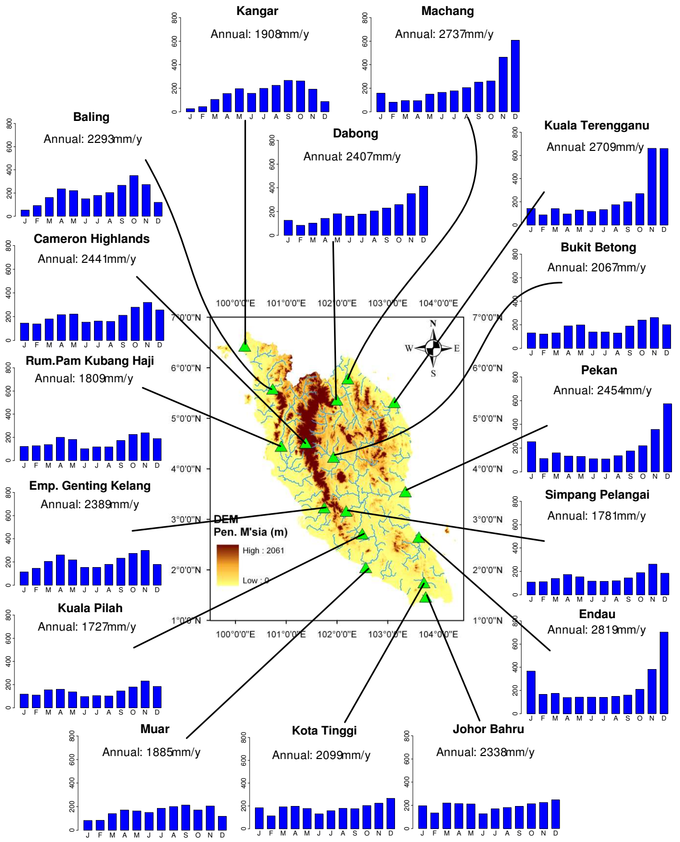

Fig. 3. Mean monthly and annual rainfall at sixteen selected stations in Peninsular Malaysia. The background map displays the orography of the area.

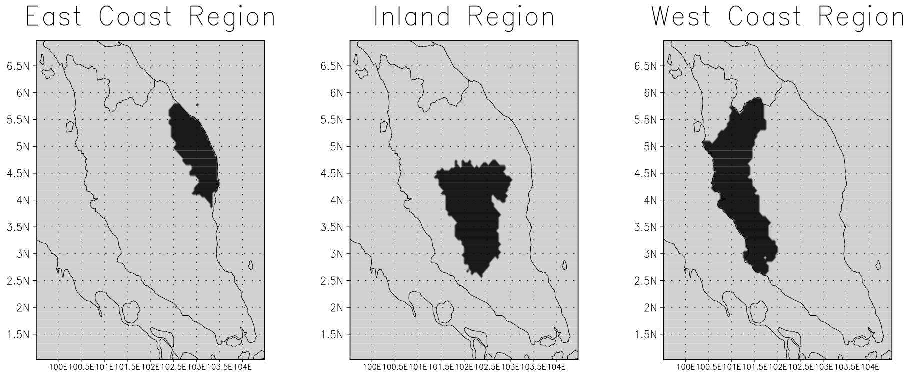

Fig. 4. Three selected distinct regions of Peninsular Malaysia.

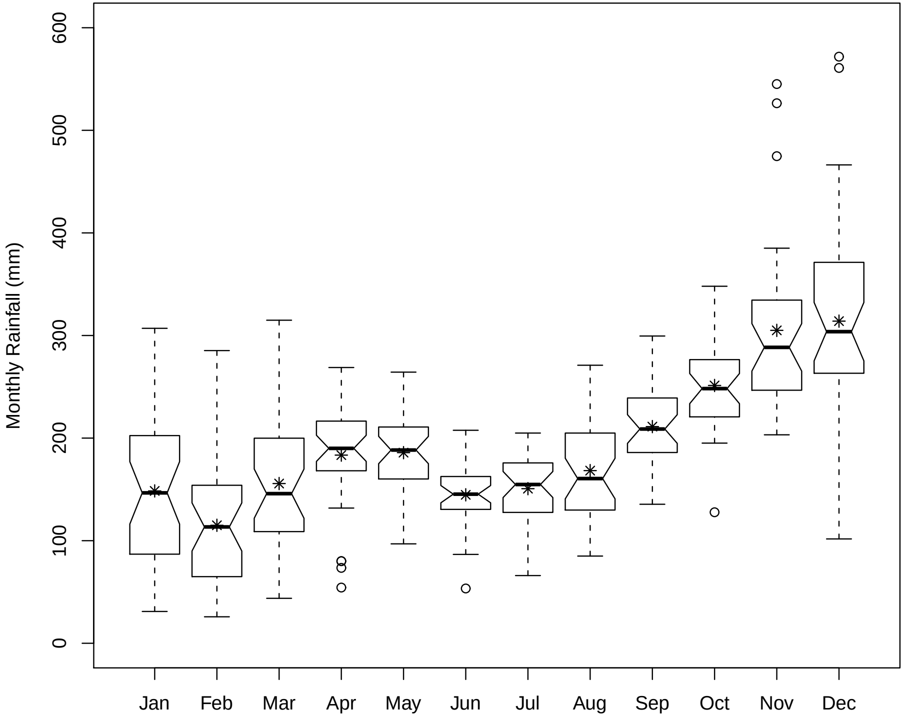

Fig. 5. Box and whisker plot of areal average mean monthly rainfall (1971–2006) in Peninsular Malaysia (after Wong et al., 2009). The asterisk denotes the mean value, the solid line is the median, the height of the box is the difference between the third and first quartiles (IQR). Any data observation which lies 1.5 IQR lower than the first quartile or 1.5 IQR higher than the third quartile can considered an outlier in the statistical sense, indicated by open circles.

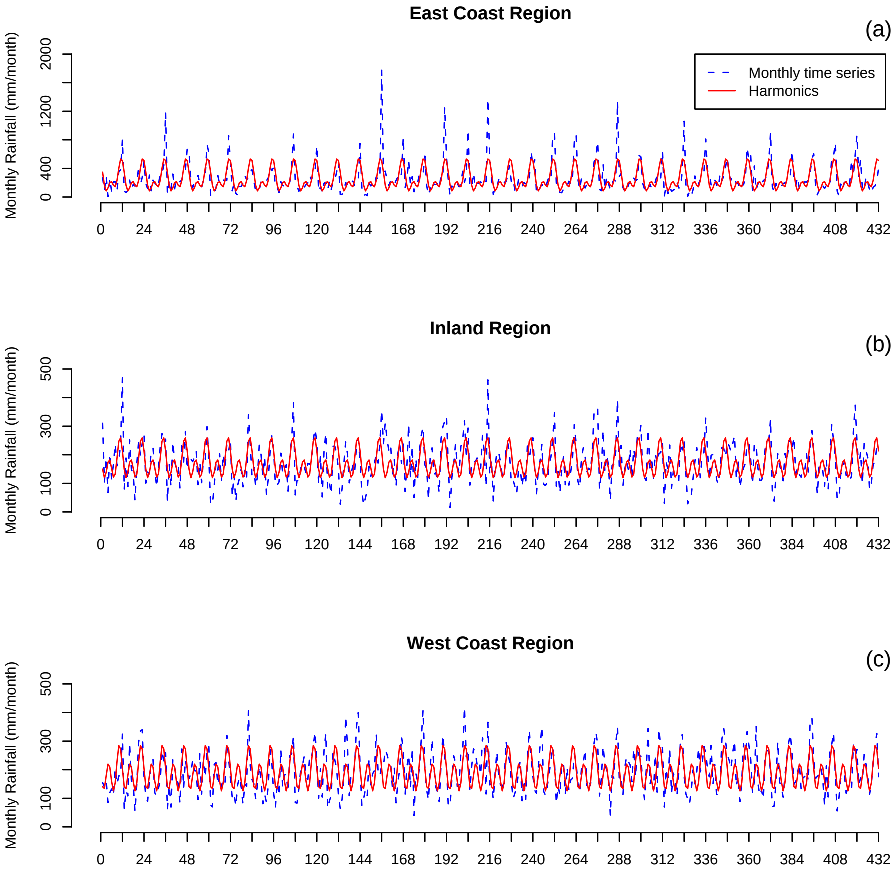

Fig. 6. Fit of harmonics to the monthly regional rainfall time series for **(a)** the east coast, **(b)** the inland, and **(c)** the west coast region.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

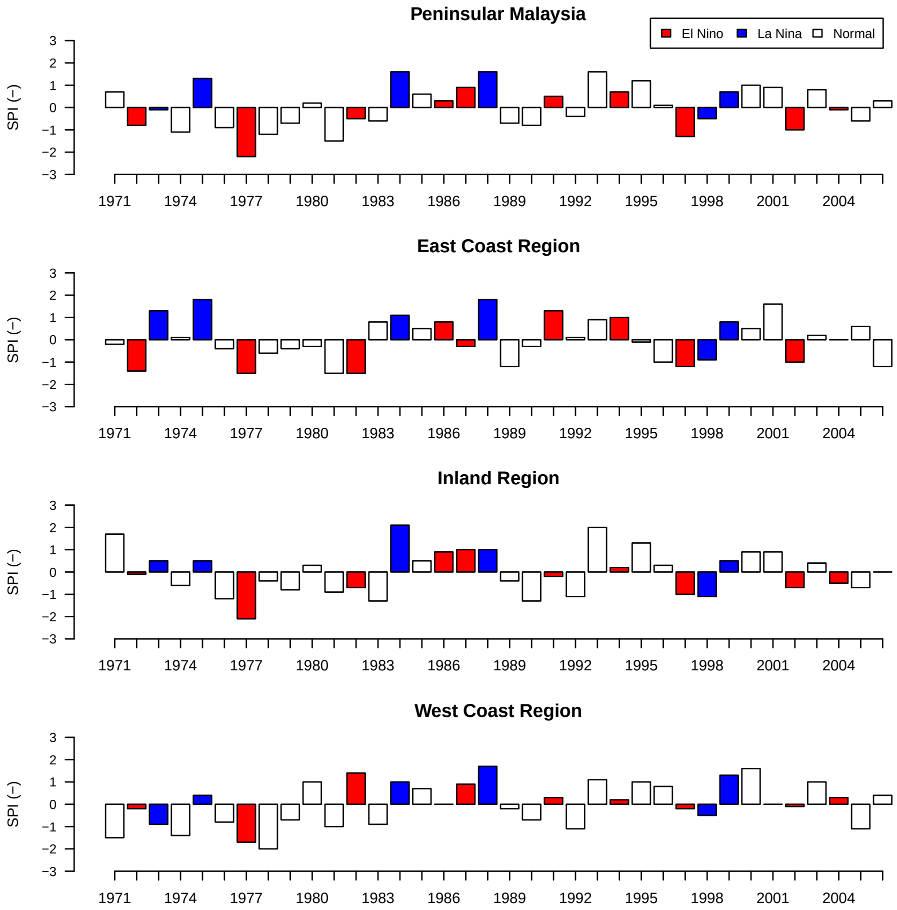

Fig. 7. Long-term standardized rainfall anomaly for Peninsular Malaysia and three regions.

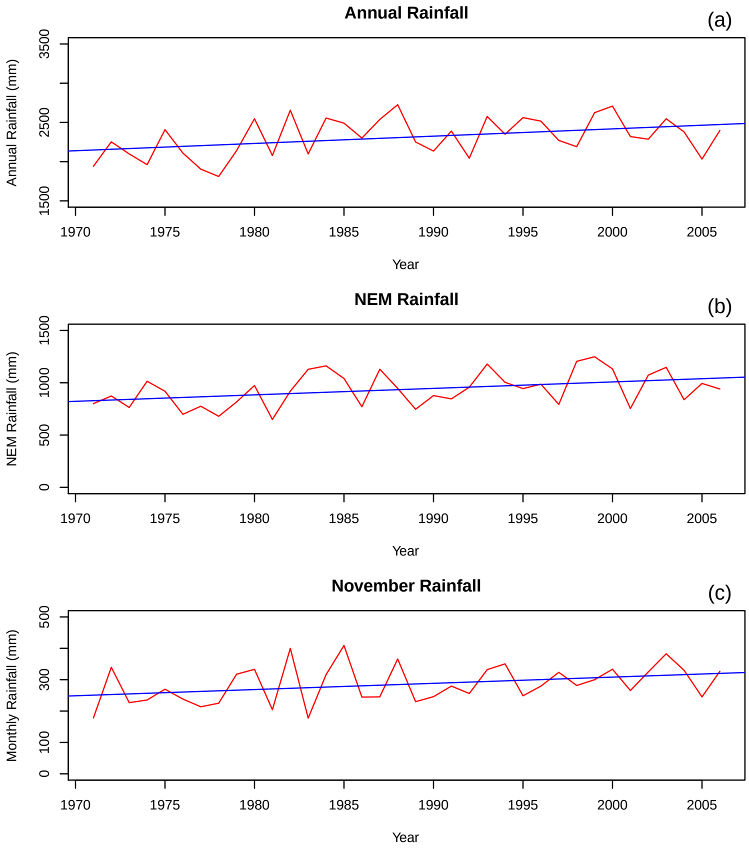

Fig. 8. Rainfall trends in annual, NEM and November rainfall in the west coast region.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
|◀
▶|
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

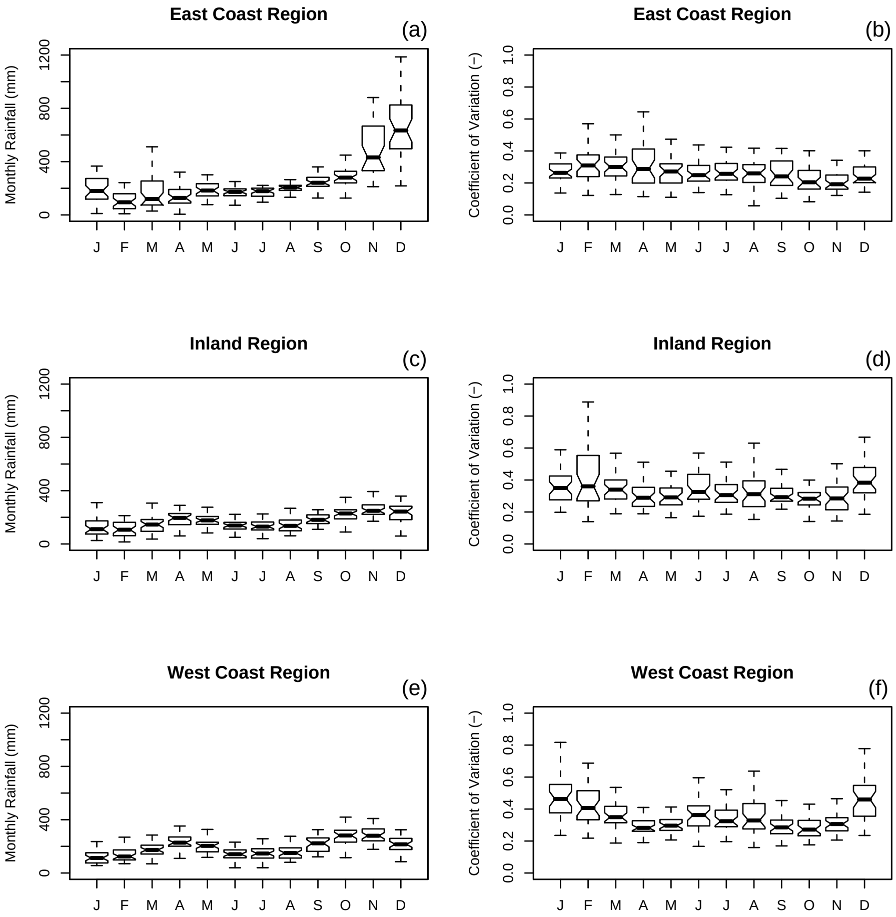

Fig. 9. Box plots of mean monthly rainfall (left side) and mean monthly coefficients of variation (right side) for the east coast, inland and west coast region.