Check for updates

Water Supply

IWA PUBLISHING

Water Supply Vol 22 No 5, 4757 doi: 10.2166/ws.2022.140

Spatio-temporal analysis of precipitation, temperature and drought from 1985 to 2020 in Penang, Malaysia

Mou Leong Tan[a,*], Fei Zhang[b], Chan Juinn Chieh Derek[c], Kok Hwa Yu[d], Shazlyn Milleana Shaharudin[e], Ngai Weng Chan[a] and Abdul Rahim Asyirah[a]

[a] GeoInformatic Unit, Geography Section, School of Humanities, Universiti Sains Malaysia, Gelugor, Penang 11800, Malaysia
[b] Key Laboratory of Wisdom City and Environmental Modeling of Higher Education Institute, College of Geographical Science, Xinjiang University, Urumqi 830046, China
[c] School of Chemical Engineering, Universiti Sains Malaysia, Nibong Tebal, Penang 14300, Malaysia
[d] School of Mechanical Engineering, Universiti Sains Malaysia, Nibong Tebal, Penang 14300, Malaysia
[e] Department of Mathematics, Faculty of Science and Mathematics, Universiti Pendidikan Sultan Idris, Tanjong Malim, Perak 35900, Malaysia
*Corresponding author. E-mail: mouleong@usm.my

MLT, 0000-0003-3939-0336

ABSTRACT

This study aims to analyze the spatial and temporal variability of precipitation, temperature and drought in Penang from 1985 to 2020. The trend and magnitude changes in climate series were tested using the Mann–Kendall test and Sens' slope methods. A significant increasing trend of annual precipitation was detected in the middle and northern parts of Penang mainland by 21.38 and 35.01 mm/decade. Annual mean maximum temperature increased significantly on Penang Island and the middle of Penang mainland at the rates of 0.25 and 0.34 °C/decade, while annual mean minimum temperature increased significantly for all stations from 0.36 to 0.52 °C/decade, showing increases of warm nights in the past few years. Extreme drought events (SPI-3 > -2) over Penang were mostly occurred during the strong El Niño years, e.g. 1988–1989, 1997–1998, 2010–2011 and 2014–2016. The number of drought events is higher during the 2001–2010 (4–11 events) period as compared to the 1991–2000 (6–9 events) and 2011–2020 (7–8 events). Interestingly, the 2011–2020 period tends to have a shorter drought duration, but more intense droughts have been observed, particularly on Penang Island and the northern and southern parts of Penang mainland.

Key words: climate change, drought, precipitation, temperature, trend

HIGHLIGHTS

- Annual precipitation had a significant increasing trend in middle and northern Penang mainland.
- Min temperature was increased significantly at a higher rate than max temperature.
- More intense droughts were found in Penang Island, middle and southern Penang mainland.
- Drought formation over Penang is closely related to precipitation and max temperature.
- SPI and SPEI have not much difference in tropical drought analysis.

INTRODUCTION

Dynamic changes in precipitation and temperature have led to changes in drought characteristics across the globe (Ahmed *et al.* 2018; Venkata *et al.* 2020). Droughts can last for weeks, months, years and even decades (Xu *et al.* 2015), which have significant impact on agricultural sectors, water resources, socio-economic and human health. In the latest Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) (IPCC 2021), natural disaster events such as heavy precipitation, heatwaves, and droughts have been increasing since 1950s in different parts of the world. In Southeast Asia, droughts have affected more than 66 million people in the past 30 years, particularly during the El Niño years (UN and ASEAN 2019). Therefore, understanding of climate extremes and drought characteristics are important to strengthen drought risk assessment and early warning system development for building drought resilience.

Numerous drought indices have been established to quantify and monitor drought events. Standardized Precipitation Index (SPI) (McKee 1993) that was recommended by the World Meteorological Organization (WMO), is one of the most popular drought indices due to easy to use and requires only monthly precipitation data. The index can be used not only to quantify drought events, but also to estimate their duration, severity and intensity. Conversely, the Standardized Precipitation Evapotranspiration Index (SPEI) that considers potential evapotranspiration is also commonly used in drought quantification (Vicente-Serrano *et al.* 2010). Some researchers have argued that SPEI takes temperature into account and therefore is superior than SPI in drought monitoring. However, SPI is still a considerable drought index because there is not much differences in drought quantification between SPI and SPEI. For instance, Tefera *et al.* (2019) found a high level of agreement between SPI and SPEI in assessing drought in Tigray located in Northern Ethiopia. Luhaim *et al.* (2021) also reported the temporal variability of droughts of the Muda River Basin in the northern part of Peninsular Malaysia as measured by both SPI and SPEI matched quite well. Only the average drought peak and intensity of SPIE were slightly lower than the SPI. Therefore, SPI was selected to represent drought in this study.

Many studies have reported that climate and/or droughts have become more intense and frequent in Southeast Asia over the past few decades, e.g., Thailand (Sharma & Babel 2014), Vietnam (Stojanovic *et al.* 2020), Malaysia (Tan *et al.* 2021) and Singapore (Li *et al.* 2016; Jiang *et al.* 2021). In Malaysia, some studies have been conducted to evaluate the trends and characteristics of local climate system and droughts (Eli *et al.* 2012; Sa'adi *et al.* 2017; Luhaim *et al.* 2021) because the information is critical for designing more accurate climate adaptation plans and water resources management systems (Tan *et al.* 2019). Penang is among the most urbanized states in Malaysia, but is categorized as a 'water-stress' state (Chan *et al.* 2021). In fact, about 80% of the Penang's freshwater supply was extracted from the Muda River.

El Niño-Southern Oscillation (ENSO) has extensively affected the precipitation extremes in Malaysia, with anomalous wet conditions during La Niña and anomalous dry conditions in El Niño (Tangang *et al.* 2017). Based on the United States National Oceanic Atmospheric Administration (NOAA)'s Niño3.4 index value of more than 2 °C, Tangang *et al.* (2017) and Tan *et al.* (2021) have defined 1972–1973, 1982–1983, 1997–1998 and 2015–2016 as strong El Niño years. In fact, the strong El Niño events in 1997–1998 and 2015–2016 have resulted in prolonged droughts and led to water crises in many regions of Malaysia, including Penang. Yang *et al.* (2020) have evaluated monthly precipitation changes of Penang from 2003 to 2018 and found significant increases in precipitation in May, September and November, whereas a decreasing trend was detected in March. However, research to date has not yet determine the detailed long-term climate and drought assessment over Penang, thus it is necessary to systematically investigate their changes over the past few decades.

Climate changes vary by regions and populations, but no in-depth study on precipitation, temperature and drought using long-term time series data is available for this tropical urban city. Precipitation changes will influence hydrological cycle and water supply, particularly in the hydrological design and parameterization. In addition, it is important for IPCC authors to understand the state-of-art changes of tropical urban climate systems and their influence on local water supply. More climate change research is essential to enhance the climate knowledge of Penang, as well as support early drought warning development for achieving the goal as a sustainable city by 2030. Therefore, this study aimed to evaluate the spatio-temporal changes of precipitation, temperature and droughts of Penang from 1985 to 2020. This study tries to answer three important research questions: (1) What is the rate of change in precipitation and temperature in Penang in the last 36 years? (2) What are the characteristics of drought over Penang in the past 36 years? and (3) Which climate variables have a greater impact on the drought occurrence in Penang? The quantified climate and drought changes will help the local stakeholders and scientists to understand the mechanism of the historical drought which will be useful for future drought projections. Besides that, this study also compares SPI and SPEI in calculating drought to identify which index is more suitable for drought monitoring in tropical region.

STUDY AREA

Penang is located in the north-western part of Peninsular Malaysia, between longitudes 100°10′E to 100°35′E and latitudes 5°5′N to 5°35′N (Figure 1). The state is divided into Penang Island (293 km^2) and Penang mainland (751 km^2) by the Penang Straits. Penang hill in the central part of the island is the highest point of Penang, with a height of 833 m. In 2018, major land use land cover types of Penang were urban (34.22%), agricultural (32.59%), forest (32.15%) and water bodies (1.04%) (Tew *et al.* 2019). Urban areas are mainly distributed in the eastern part of Penang Island and the middle part of Penang mainland. The total population and population density of Penang in 2020 were 1.77 million and

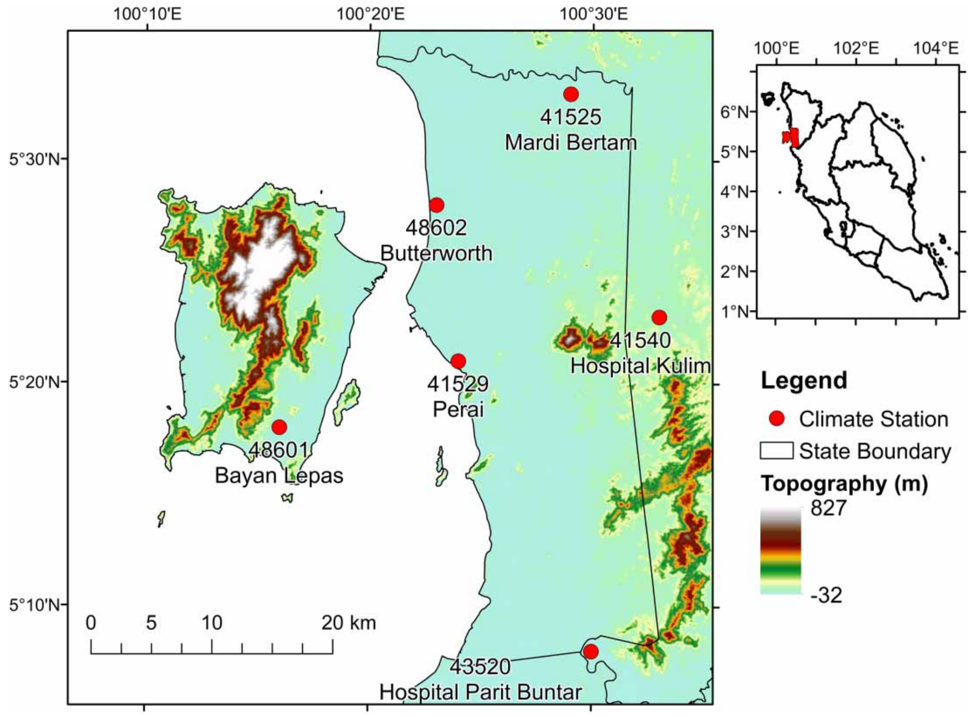

Figure 1 | Topography and distribution of climate stations over Penang.

1,687/km^2, respectively. Penang has a tropical rainforest climate system that is characterized by abundant annual precipitation and hot temperatures. The climate system of Penang is influenced by the Southwest Monsoon (SWM) from May to September, the Northeast Monsoon (NEM) from November to March, and two inter-monsoons in April and October (Tan *et al.* 2021).

MATERIALS AND METHODS

Data acquisition

Daily precipitation, maximum and minimum temperatures data from 1985 to 2020 at six meteorological stations were collected from Malaysia Meteorological Department (MMD). The Hospital Parit Buntar station was excluded from the temperature analysis because its temperature data have been only available since 2017. According to the WMO, a minimum of 30 years' data are needed for identifying the evidence of climate change. Hence, these stations were selected based on the length of data period (>30 years) and contain less than 5% missing values. For instance, the Muda Head (USM) station which is located in the north-western part of Penang Island was excluded from this analysis since the station only started to operate in 2003. The selected meteorological stations are well distributed over Penang as shown in Figure 1 and their information is listed in Table 1.

Standardized Precipitation Index (SPI)

SPI is a drought index widely applied around the world to quantify drought for different time scales (McKee 1993). It is calculated from the historical precipitation collected from MMD as described in the previous section. The SPI generator tool developed by the National Drought Mitigation Center was used to calculate SPI for a three-month time scale (SPI-3) to understand precipitation anomalies over three months. As Malaysia is a tropical region, a deficit of one-month precipitation would not impact significantly on the environment, therefore, SPI-3 was selected for the drought assessment. Table 2 shows the classification of climate conditions based on the SPI values, where positive SPI values represent wet conditions and negative SPI values represent dry conditions. The SPI values less than −1, −1.5 and −2 can be represented as moderate dry, severely dry and extremely dry conditions, respectively.

Five drought characteristics, e.g. frequency, duration, peak, severity and intensity, were calculated for the periods of 1991–2000, 2001–2010 and 2011–2020 to compare their changes in the last three decades. Drought frequency refers to the number

Table 1 | Climate stations over Penang and their climate variables annual mean value

ID	Name	Latitude (N)	Longitude (E)	Elevation (m)	Total rainfall (mm/year)	Maximum temperature (°C)	Minimum temperature (°C)
41525	Mardi Bertam	5.55	100.48	7.30	2,320.72	32.69	23.82
41529	Perai	5.35	100.40	1.00	2,183.35	32.18	24.63
41540	Hospital Kulim	5.38	100.55	32.00	2,667.77	32.83	23.21
43520	Hospital Parit Buntar	5.13	100.50	3.10	2,055.27	–	–
48601	Bayan Lepas	5.30	100.27	3.00	2,351.61	31.64	25.53
48602	Butterworth	5.47	100.38	2.00	2,275.86	31.96	24.09

Table 2 | SPI classification

SPI	Classification
>2.00	Extremely wet
1.50 to 1.99	Severely wet
1.00 to 1.49	Moderately wet
0.99 to -0.99	Near normal
-1.00 to -1.49	Moderately dry
-1.50 to -1.99	Severely dry
<-2.00	Extremely dry

of drought that have occurred during the evaluated period, while drought duration indicates the time period of a specific drought event. Drought peak refers to the lowest SPI value for a specific drought event, whereas drought severity is the sum of the SPI values. Drought intensity is calculated by dividing drought severity with drought duration. A detailed description of the drought characteristics calculation is also available in similar studies conducted in the Muda River Basin (Luhaim *et al.* 2021) and the Sarawak River Basin (Bong & Richard 2019) in Malaysia.

Trend and magnitude analysis

The non-parametric Mann–Kendall (MK) and Sen's slope tests were used for the trend detection and magnitude change analysis. Both the MK and Sen's slope tests have been widely applied in climate extremes around the world (Tong *et al.* 2019; Tan *et al.* 2021). WMO has recommended the MK test as the indicator to check whether the trend of hydro-climatic changes is significant or otherwise. Null hypothesis of the MK test states that there is no trend in the hydro-climatic data. By contrast, a monotonic trend of data can be identified if an alternative hypothesis is accepted. In general, there is an alternative hypothesis in which a climate extreme trend was detected at 95% confidence level when Z values were greater than ± 1.96. Positive Z values show an increasing trend, while negative Z values indicate a decreasing trend. The MK test can be calculated using the following equations:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \tag{1}$$

$$\operatorname{sgn}(x_j - x_k) = \begin{cases} +1, & \textit{if} \quad (x_j - x_k) > 0 \\ 0, & \textit{if} \quad (x_j - x_k) = 0 \\ -1, & \textit{if} \quad (x_j - x_k) < 0 \end{cases} \tag{2}$$

where x_j and x_k are the sequential data values, while sgn is the signal of the difference of subsequent tested hydro-climatic variables. Statistic S approximates to normal distribution if n is greater than 8. The variance of S and the MK statistic z

are calculated as:

$$\mathrm{var}(S) = \frac{n(n-1)(2n+5)}{18} \tag{3}$$

$$z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{var}(S)}}, & \text{if} \quad S > 0 \\ 0, & \text{if} \quad S = 0 \\ \frac{S+1}{\sqrt{\mathrm{var}(S)}}, & \text{if} \quad S < 0 \end{cases} \tag{4}$$

Conversely, Sen's slope is able to provide the information on the rate of change by year. To obtain decadal changes, the Sen's slope values are then multiplied with 10. It can be calculated as follows:

$$\beta = med\frac{x_j - x_k}{j - k}, j > k \tag{5}$$

where β is Sen's slope with positive and negative values that shows increasing and decreasing trends in a time series, respectively, whereas med refers to median.

RESULTS AND DISCUSSION

Spatio-temporal changes in precipitation

Total precipitation and mean temperature changes on the annual and monthly scales over Penang for the 1985–2020 period are shown in Figure 2. Annual total precipitation amounts over Penang were ranging from 1,347.20 mm/year in 2002 to

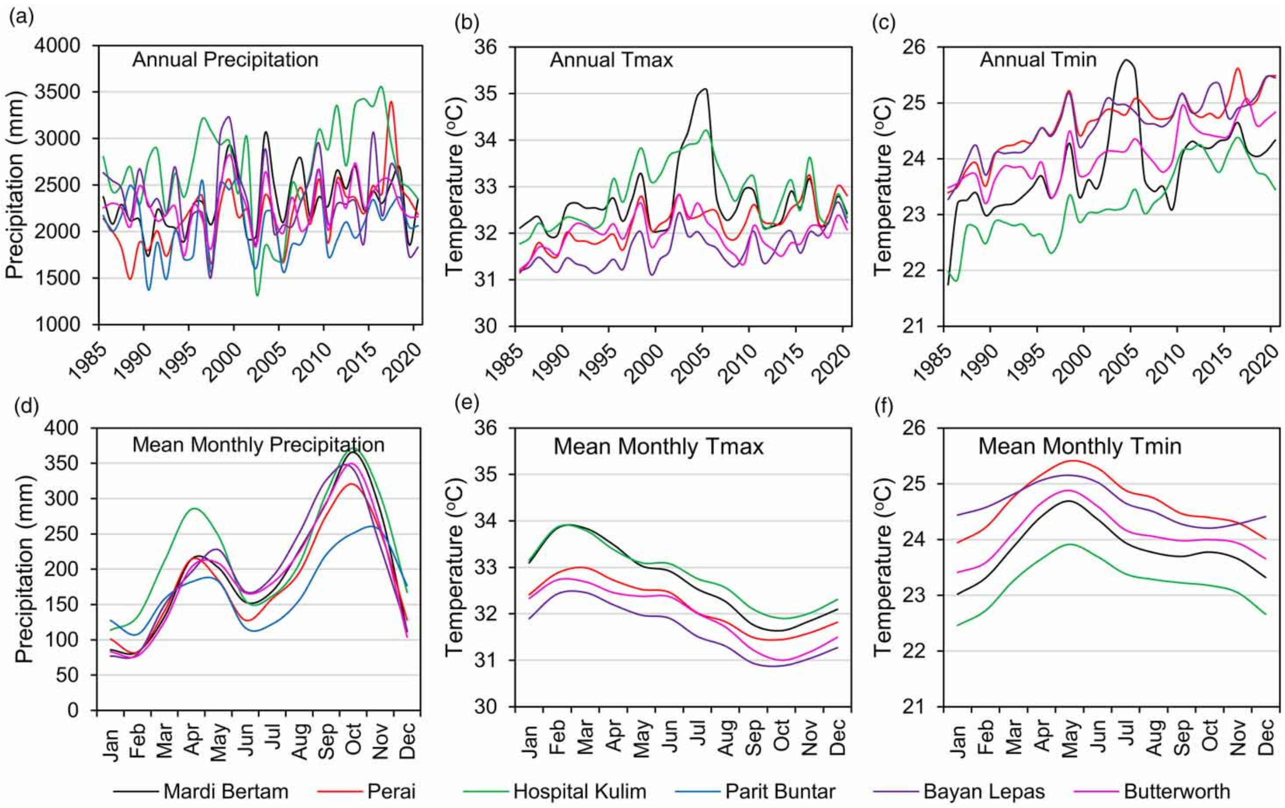

Figure 2 | Annual and mean monthly (a, d) precipitation, (b, d) maximum temperature and (c, f) minimum temperature at various climate stations over Penang from 1985 to 2020.

3,548.20 mm/year in 2016 (Figure 2(a)). A relatively lower annual precipitation rate, with more than 50% of the stations having less than 2,000 mm/year, can be observed in 1997, 2002 and 2005 (Figure 2(a)). Hospital Kulim has received a higher annual precipitation compared to other stations, while a lower value was found at Hospital Parit Buntar. Figure 3 indicates that annual precipitation of Perai and Mardi Bertam have been increased significantly at 95% confidence level, at a rate of 35.01 and 21.38 mm/decade, respectively. This shows that the changes of annual precipitation tended to be more significant over Penang mainland than Penang Island.

Penang is less influenced by the NEM because the Titiwangsa range causes heavy precipitation to rapidly decrease from east to west (Jamaludin *et al.* 2010). Due to its geographical location, Penang receives more precipitation during the inter-monsoon periods in April and October as shown in Figure 2(d), which is known as a bimodal annual precipitation distribution. In addition, Penang also receives a relatively higher precipitation amount during the SWM compared with other regions in Malaysia (Wong *et al.* 2016). This is due to the exposure of Penang to the SWM influence, while other regions of the west coast Peninsular Malaysia are shielded by the mountain ranges in Sumatra. Table 3 shows that monthly

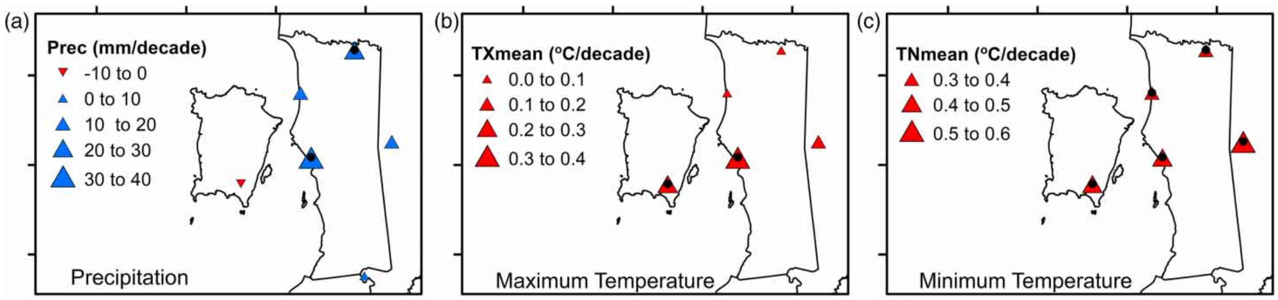

Figure 3 | Magnitude changes of annual precipitation and annual mean temperature at various climate stations over Penang from 1985 to 2020.

Table 3 | Magnitude changes of monthly precipitation, maximum and minimum temperature of Penang from 1985 to 2020

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation (mm/decade)												
Mardi Bertam	7.18	9.64	5.74	14.94	26.91	−4.77	20.55	**−26.34**	−2.16	−1.46	27.96	**22.48**
Perai	5.30	15.26	−16.23	20.64	27.80	6.00	2.60	2.46	27.18	21.89	38.72	**20.56**
Hospital Kulim	21.47	13.25	−12.36	0.55	**33.77**	−16.44	−5.58	12.08	13.54	−28.20	25.81	22.37
Parit Bunta	13.23	7.44	−24.42	−4.71	5.47	5.19	12.91	−17.56	20.69	−6.39	11.70	7.25
Bayan Lepas	6.72	−10.42	−11.53	−13.21	9.47	−6.19	5.10	−33.79	−13.33	−30.39	5.60	5.04
Butterworth	14.79	−1.89	−12.16	2.80	6.00	−9.15	13.73	**−35.14**	−8.89	−0.41	28.43	**21.50**
Maximum temperature (°C/decade)												
Mardi Bertam	−0.12	0.11	0.20	0.03	0.08	0.02	0.09	**0.23**	**0.21**	0.20	0.10	−0.09
Perai	**0.32**	**0.38**	**0.48**	**0.35**	**0.32**	**0.25**	**0.29**	**0.38**	**0.40**	**0.45**	**0.35**	0.21
Hospital Kulim	0.19	0.19	**0.41**	**0.34**	0.21	0.20	0.16	0.24	0.18	0.21	0.16	0.05
Bayan Lepas	0.09	**0.27**	**0.43**	**0.22**	**0.17**	**0.21**	**0.27**	**0.40**	**0.38**	**0.38**	**0.25**	0.08
Butterworth	−0.18	0.13	0.13	0.04	0.05	−0.02	0.07	**0.22**	0.16	0.11	0.08	−0.12
Minimum temperature (°C/decade)												
Mardi Bertam	**0.45**	**0.47**	**0.43**	**0.35**	**0.28**	**0.33**	**0.41**	**0.35**	**0.36**	**0.39**	**0.39**	**0.46**
Perai	**0.58**	**0.36**	**0.59**	**0.33**	**0.40**	**0.43**	**0.53**	**0.47**	**0.38**	**0.39**	**0.39**	**0.49**
Hospital Kulim	**0.76**	**0.51**	**0.66**	**0.38**	**0.32**	**0.50**	**0.59**	**0.50**	**0.44**	**0.43**	**0.53**	**0.76**
Bayan Lepas	**0.43**	**0.43**	**0.57**	**0.42**	**0.40**	**0.45**	**0.53**	**0.49**	**0.45**	**0.37**	**0.37**	**0.30**
Butterworth	**0.40**	**0.26**	**0.42**	**0.31**	**0.31**	**0.34**	**0.40**	**0.33**	**0.37**	**0.37**	**0.39**	**0.43**

Bold text represents significant changes at 95% confidence level.

precipitation in December for the stations located in the middle and northern parts of Penang increased significantly at the rates of 20.56–22.48 mm/decade. According to the analysis, monthly precipitation of August has decreased significantly at the rates of −26.34 to 35.41 mm/decade in the northern part of Penang. Monthly precipitation rates in January, May and November at all stations have increased insignificantly at the rates of 5.30–21.47 mm/decade, 5.47–33.77 mm/decade and 5.60–38.72 mm/decade, respectively. In general, no significant changes in monthly precipitation were found at most of the stations in other months.

Spatio-temporal changes in temperatures

Annual mean maximum and minimum temperatures for Penang from 1985 to 2020 were ranged from 31.65 to 32.83 °C and 23.21 to 24.63 °C, respectively (Figure 2). Similar to other tropical regions, Penang is warm throughout the year and has a small variation in annual temperature range. Due to the climate change effect, a significant increasing trend of annual mean maximum temperature was found in Bayan Lepas and Perai, with the rates of 0.25 °C/decade and 0.34 °C/decade, respectively (Figure 3(b)). In addition, annual mean minimum temperature decreased significantly at all the five climate stations, ranging from 0.36 °C/decade to 0.52 °C/decade. In general, minimum temperature tended to increase at a higher rate than maximum temperature, showing increases in the number of warm nights over Penang in the past few decades. The finding is consistent with a national scale temperature trend analysis that conducted by Tan *et al.* (2021).

Similar to the annual scale, monthly mean maximum temperature at the Bayan Lepas and Perai stations had also increased significantly at the rates of 0.17–0.45 °C/decade, except for December (Table 3). The result may be explained by the fact that both the stations are surrounded by high density housing and factories. A similar phenomenon was also found in the capital of Malaysia, Kuala Lumpur (Ramakreshnan *et al.* 2018), which clearly indicates that the rapid urbanization has caused the climate change become worse in major cities. Table 3 also shows that a significant increasing trend of monthly mean minimum temperature was found at all the five stations for all months during the 1980–2020 period, ranging from 0.26 to 0.76 °C/decade. A comparative higher rate of change in monthly mean minimum temperature was observed in January, March, July and December, which received lesser monthly precipitation than other months.

Spatio-temporal changes in drought

The temporal changes in SPI-3 at each meteorological station from 1985 to 2020 over Penang are shown in Figure 4. The formation of the extreme droughts in Penang was closely related to El Niño (Luhaim *et al.* 2021; Tan *et al.* 2021) because the occurrences of these events were mostly recorded during the strong El Niño years, e.g. 1988–1989, 1997–1998, 2010–2011 and 2014–2016. For instance, an extreme drought event was observed at all the climate stations during the 1997–1998 El Niño, which is associated with extremely low precipitation and high temperature conditions as shown in Figure 2. In general, a non-significant trend of SPI-3 was found at most of the stations.

Figure 5 shows the spatial distribution of monthly SPI-3 over the 1985–2020 period in Penang. A significant increasing trend in SPI-3 at a 95% confidence level was detected in January and February at various stations. Perai and Mardi Bertam are the only climate station experienced significant increasing trends of SPI-3 in the months other than January and February. For example, the Perai station also showed a significant increasing trend of SPI-3 in June, November and December, whereas, the Mardi Bertam station in May and July. The remaining stations have experienced non-significant changes in SPI-3 in almost every month, except February. Basically, the significant changes in monthly SPI-3 were found in the middle and norther parts of Penang mainland.

Drought characteristics

Figure 6 shows the drought characteristics for the recent three decades over Penang using the SPI-3 as drought indicator. Generally, the drought frequency of Penang was higher in the 2001–2010 (4–11 events) period as compared with the 1991–2000 (6–9 events) and 2011–2020 (7–8 events) periods. Interestingly, the most recent decade period of 2011–2020 tended to have shorter drought durations for most of the stations, except for Butterworth. A possible explanation for these results may be due to the increases in the monthly precipitation from November to December and May, as illustrated in Table 3. Surprisingly, the longest drought duration of 31 months was recorded at the Hospital Kulim station during the 2001–2010 period, while the other stations only ranged from 5 to 12 months. The year 2002 was one of the most critical hydrological drought years in Malaysia, particularly in the northern region. The Hospital Kulim station has received extremely low amounts of total precipitation from 2002 (1,347.2 mm/year) to 2005 (1,692.7 mm/year), which was less than its mean value of 2,667.77 mm/year as shown in Figure 2(a). The low amount of annual precipitation compared with other

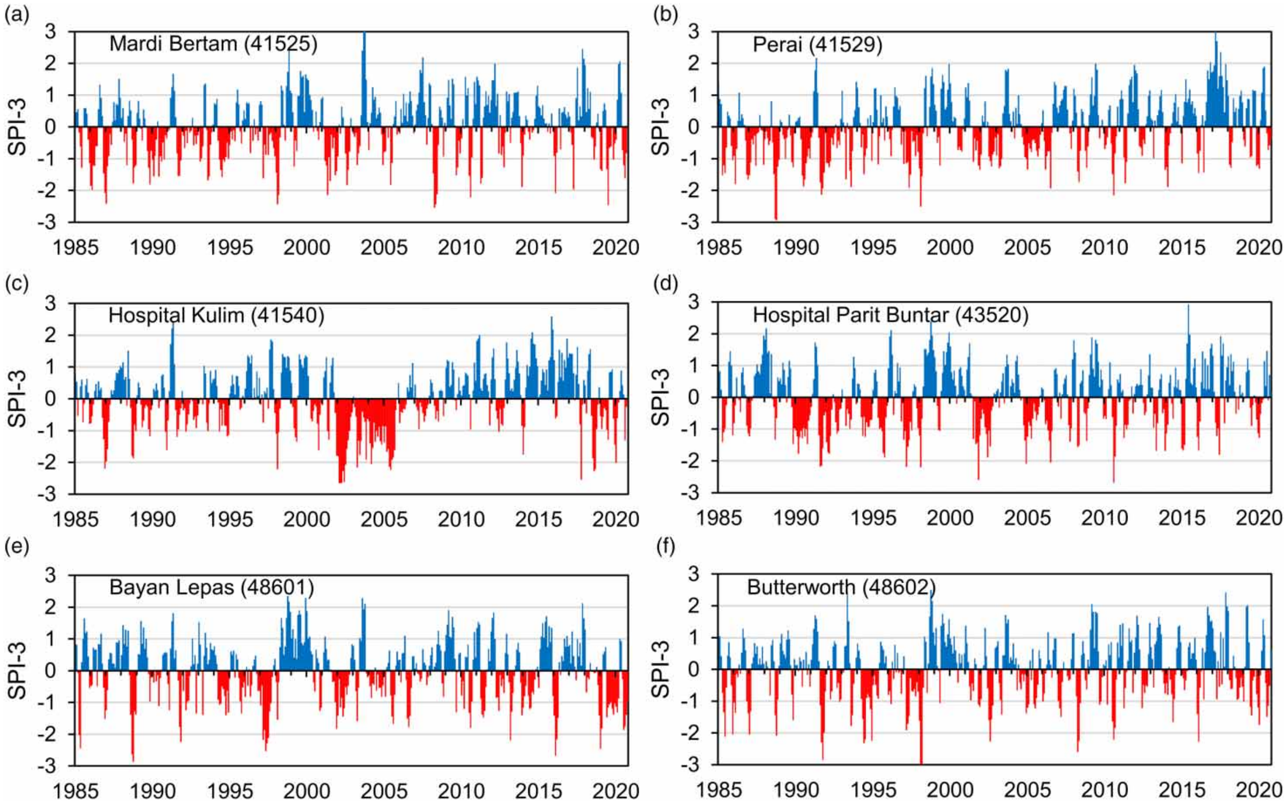

Figure 4 | Temporal changes of SPI-3 at various climate stations over Penang from 1985 to 2020.

nearby stations may be explained by two facts: (1) the location of the Hospital Kulim station is far from the coastal areas that receive more precipitation than inland; and (2) the rain shadow effect where the areas behind mountains may experience a sharp reduction in precipitation.

The highest drought peak of −3 was found at the Butterworth station during the 1991–2000 period in April 1998 due to the super El Niño effect. The drought peak at the Hospital Parit Buntar and Bayan Lepas stations was higher in the recent decade (2011–2020) than the previous two decades. The severity of drought seems to reduce slightly over time at most of the stations, except the Hospital Kulim station. The Mardi Bertam, Hospital Parit Buntar and Bayan Lepas stations had a higher drought intensity during the 2011–2020, showing that more intense droughts had occurred more recently on Penang Island and in the northern and southern parts of Penang mainland. These results are likely to be related to the drier condition during the months of the SWM season in the northern Peninsular Malaysia since the last three decades (Wong *et al.* 2016). Therefore, climate adaptation strategies such as planting more trees, installation of rainwater harvesting systems, organization of climate awareness campaigns should be implemented to reduce the impact of global warming in Penang.

Relationship between climate and drought

To understand which climate variable has a greater impact on the drought formation over Penang in the past 36 years, the relationships of precipitation, maximum and minimum temperatures with drought were further investigated using the correlation coefficient (CC) method. In general, precipitation has the largest influence on the drought formation in Penang, with the correlation values ranging from 0.44 to 0.53 (Table 4). Maximum temperature also has a considerable impact on the drought formation, while minimum temperature did not show a strong relationship with drought, particularly in Mardim Bertam, Perai and Butterworth. The findings show that droughts over Penang are closely related to the changes in precipitation and maximum temperature.

SPEI was also added in this relationship assessment to investigate on how the additional of temperature in the index calculation would impact the drought analysis. Table 4 illustrates the correlation coefficient values as measured by SPI-3 and

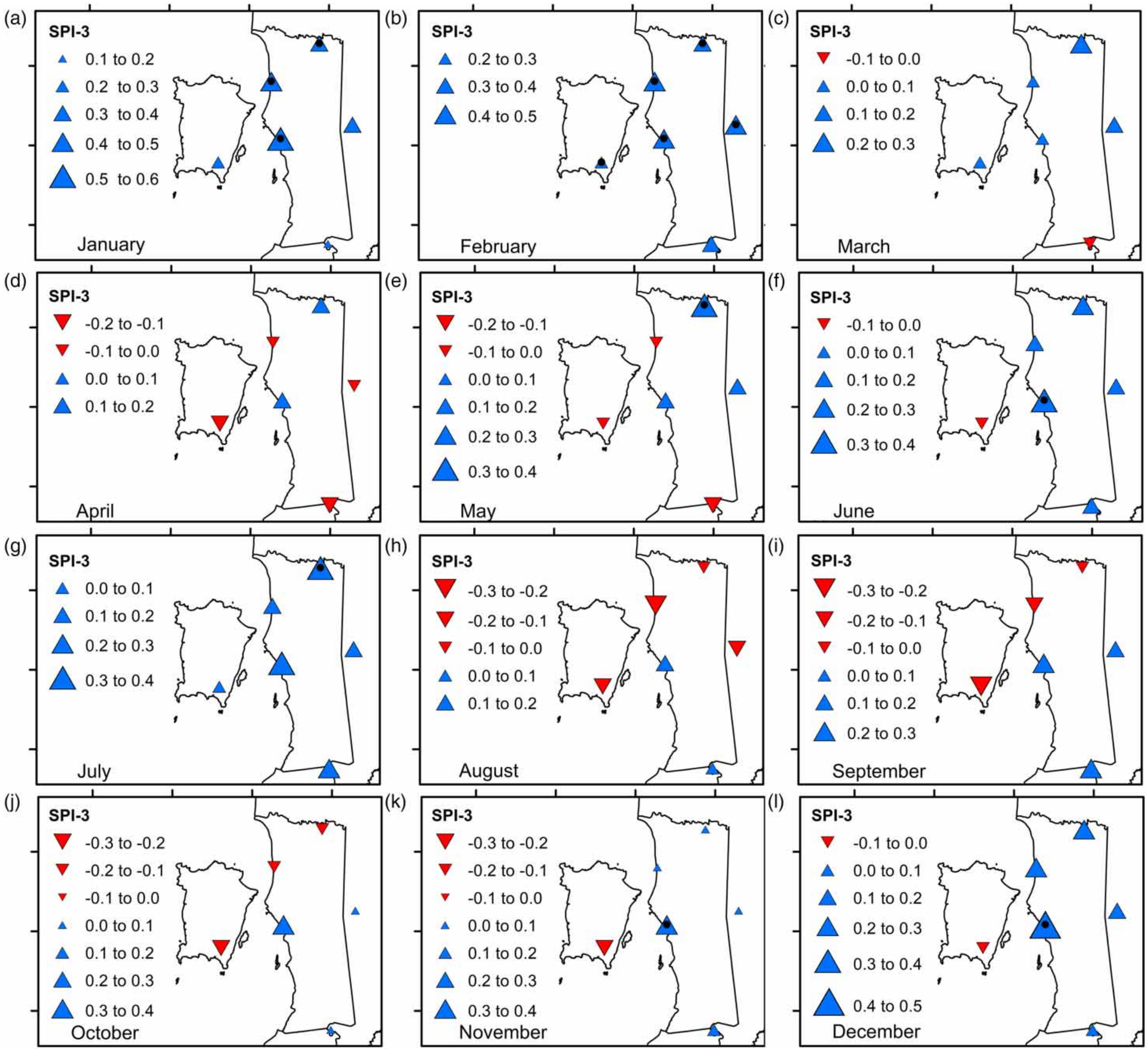

Figure 5 | Spatial changes of SPI-3 at various climate stations over Penang from 1985 to 2020.

SPEI-3 did not show significant differences, e.g. only a 0.02 difference when compared to Mardi Bertam's drought. Integration of temperature data in drought index calculation can slightly increase the relationship between climate and drought in Penang. For example, the CC values for maximum temperature and drought in Mardi Bertam increased slightly from −0.21 (SPI-3) to −0.26 (SPEI-3). A possible explanation for SPEI-3 which did not show much difference with SPI-3 in the climate relationship analysis is due to the low temperature variability in this tropical region.

CONCLUSIONS

This study quantified the changes of climate and drought over Penang from 1985 to 2020 at six well distributed climate stations. Three-month Standardized Precipitation Index (SPI-3), a widely applied drought index was used to characterize the droughts. Conversely, the MK and Sens' slope methods were applied to study the trend and magnitude changes of precipitation, maximum temperature, minimum temperature and SPI-3 in the past few decades.

In general, annual precipitation exhibited an increasing trend over Penang mainland, especially in the middle and northern regions. Annual mean maximum temperature at the Bayan Lepas and Perai stations was increased significantly at a 95%

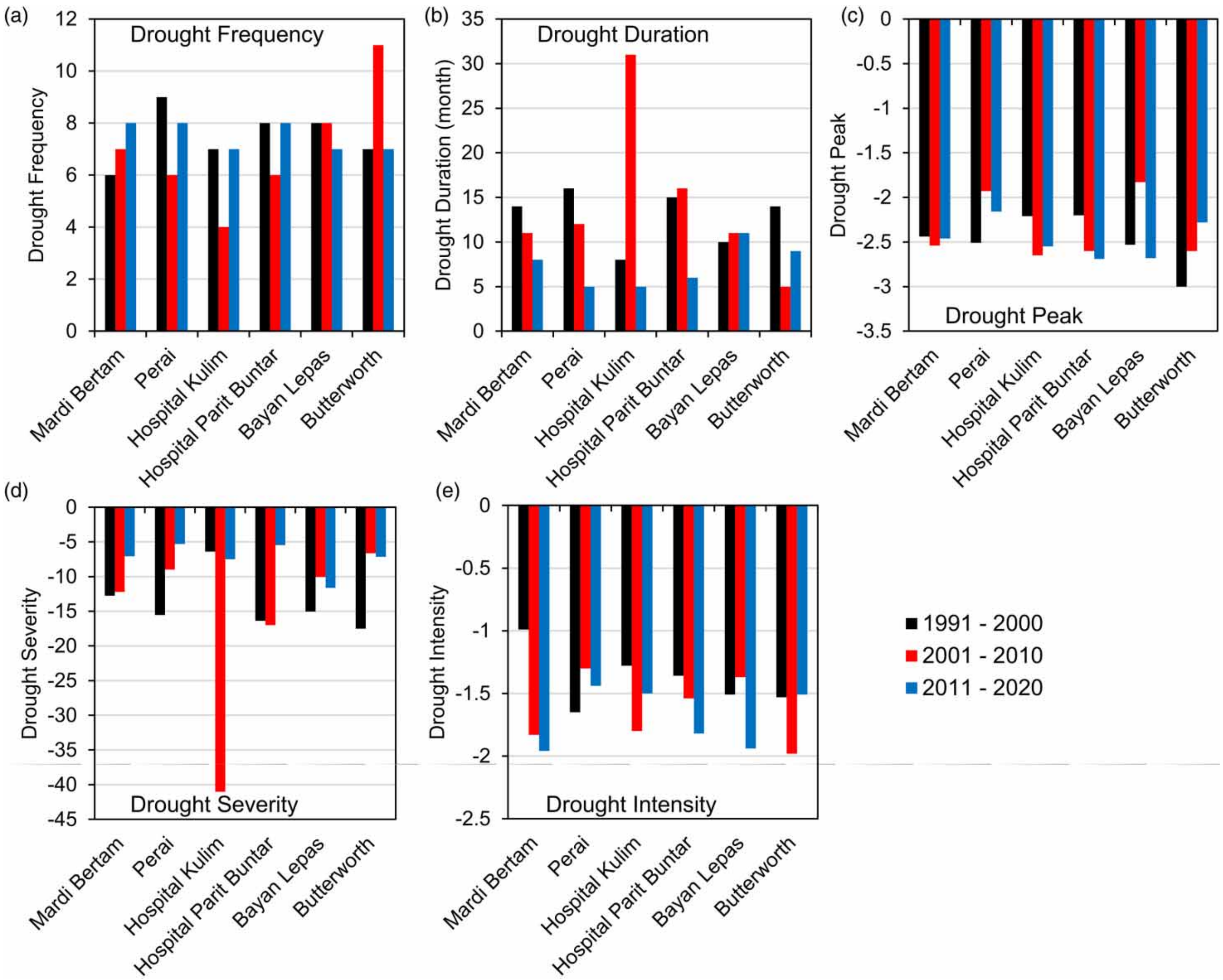

Figure 6 | Drought characteristics of various climate stations over Penang from 1990 to 2020.

Table 4 | Correlation of the SPI and SPEI with precipitation, maximum (Tmax) and minimum (Tmin) temperatures

		Mardi Bertam	Hospital Kulim	Perai	Hospital Parit Buntar	Bayan Lepas	Butterworth
SPI-3	Precipitation	0.44*	0.51*	0.48*	0.53*	0.45*	0.43*
	Tmax	−0.21*	−0.23*	−0.10*	–	−0.30*	−0.25*
	Tmin	0.03	0.16*	0.09	–	−0.19*	0.00
SPEI-3	Precipitation	0.42*	0.51*	0.47*	–	0.45*	0.42*
	Tmax	−0.26*	−0.27*	−0.12*	–	−0.31*	−0.28*
	Tmin	0.02	0.19*	0.08	–	−0.20*	0.02

Note: *represents significance at the 95% confidence level.

confidence level by 0.25 °C/decade and 0.34 °C/decade, respectively. All the evaluated stations experienced a significant increasing trend in annual mean minimum temperature, with the rates 0.36 °C/decade to 0.52 °C/decade. The greater increases in minimum temperature compared with maximum temperature resulted a smaller diurnal temperature range over Penang in the past few years.

This study confirmed that most of the extreme droughts in Penang occurred during the strong El Niño years, e.g. 1988–1989, 1997–1998, 2010–2011 and 2014–2016. With the SPI-3 as a drought indicator, the number of droughts was higher during the 2001–2010 period than the 1991–2000 and 2011–2020 periods. The drought duration in the recent decade (2011–2020) tended to be shorter compared with the previous two decades, but a greater drought intensity was observed, particularly on Penang Island and in the northern and southern parts of the Penang mainland. In addition, precipitation has the largest effect in the drought formation over Penang, followed by maximum and minimum temperatures.

ACKNOWLEDGEMENT

The project was funded by Universiti Sains Malaysia via the Division of Industry and Community Network (BJIM) grant, Project code: 1001.PHUMANITI.AUPSE00146. The authors also acknowledged the Malaysian Meteorological Department for providing climate data.

CONFLICT OF INTEREST

We declare that there is no conflict of interests regarding the publication of this article.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

REFERENCES

Ahmed, K., Shahid, S. & Nawaz, N. 2018 Impacts of climate variability and change on seasonal drought characteristics of Pakistan. *Atmospheric Research* **214**, 364–374.

Bong, C. H. J. & Richard, J. 2019 Drought and climate change assessment using Standardized Precipitation Index (SPI) for Sarawak River Basin. *Journal of Water and Climate Change* **11** (4), 956–965.

Chan, N. W., Ghani, A. A., Samat, N., Roy, R., Tan, M. L. & Rahman, H. A. 2021 *Water Security in Asia: Opportunities and Challenges in the Context of Climate Change* (Babel, M., Haarstrick, A., Ribbe, L., Shinde, V. R. & Dichtl, N., eds). Springer International Publishing, Cham, pp. 239–249.

Eli, A., Shaffie, M. & Wan Zin, W. Z. 2012 Preliminary study on Bayesian extreme rainfall analysis: a case study of Alor Setar, Kedah, Malaysia. *Sains Malaysiana* **41** (11), 1403–1410.

IPCC 2021 Summary for policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R. & Zhou, B., eds). Cambridge University, Cambridge, UK.

Jamaludin, S., Zin, W., Deni, S. & Jemain, A. 2010 Trends in Peninsular Malaysia rainfall data during the southwest monsoon and northeast monsoon seasons: 1975–2004. *Sains Malaysiana* **39**, 533–542.

Jiang, R., Li, W., Lu, X. X., Xie, J., Zhao, Y. & Li, F. 2021 Assessment of temperature extremes and climate change impacts in Singapore, 1982–2018. *Singapore Journal of Tropical Geography* **42** (3), 378–396.

Li, X., Meshgi, A. & Babovic, V. 2016 Spatio-temporal variation of wet and dry spell characteristics of tropical precipitation in Singapore and its association with ENSO. *International Journal of Climatology* **36** (15), 4831–4846.

Luhaim, Z. B., Tan, M. L., Tangang, F., Zulkafli, Z., Chun, K. P., Yusop, Z. & Yaseen, Z. M. 2021 Drought variability and characteristics in the Muda River Basin of Malaysia from 1985 to 2019. *Atmosphere* **12** (9), 1210.

McKee, T. B. 1993 The relationship of drought frequency and duration of time scales. In *Eighth Conference on Applied Climatology*, 1993, 17–22, January, Anaheim, California.

Ramakreshnan, L., Aghamohammadi, N., Fong, C. S., Ghaffarianhoseini, A., Ghaffarianhoseini, A., Wong, L. P., Hassan, N. & Sulaiman, N. M. 2018 A critical review of Urban Heat Island phenomenon in the context of Greater Kuala Lumpur, Malaysia. *Sustainable Cities and Society* **39**, 99–113.

Sa'adi, Z., Shahid, S., Ismail, T., Chung, E. S. & Wang, X. J. 2017 Trends analysis of rainfall and rainfall extremes in Sarawak, Malaysia using modified Mann–Kendall test. *Meteorology and Atmospheric Physics* **131**, 263–277.

Sharma, D. & Babel, M. S. 2014 Trends in extreme rainfall and temperature indices in the western Thailand. *International Journal of Climatology* **34** (7), 2393–2407.

Stojanovic, M., Liberato, M. L. R., Sorí, R., Vázquez, M., Phan-Van, T., Duongvan, H., Cong, T. H., Nguyen, P. N. B., Nieto, R. & Gimeno, L. 2020 Trends and extremes of drought episodes in Vietnam sub-regions during 1980–2017 at different timescales. *Water* **12** (3), 813.

Tan, M. L., Juneng, L., Tangang, F. T., Chan, N. W. & Ngai, S. T. 2019 Future hydro-meteorological drought of the Johor River Basin, Malaysia, based on CORDEX-SEA projections. *Hydrological Sciences Journal* **64** (8), 921–933.

Tan, M. L., Juneng, L., Tangang, F. T., Chung, J. X. & Radin Firdaus, R. B. 2021 Changes in temperature extremes and their relationship with ENSO in Malaysia from 1985 to 2018. *International Journal of Climatology* **41** (S1), E2564–E2580.

Tangang, F., Farzanmanesh, R., Mirzaei, A., Supari, Salimun, E., Jamaluddin, A. F. & Juneng, L. 2017 Characteristics of precipitation extremes in Malaysia associated with El Niño and La Niña events. *International Journal of Climatology* **37** (S1), 696–716.

Tefera, A. S., Ayoade, J. O. & Bello, N. J. 2019 Comparative analyses of SPI and SPEI as drought assessment tools in Tigray Region, Northern Ethiopia. *SN Applied Sciences* **1** (10), 1265.

Tew, Y. L., Tan, M. L., Samat, N. & Yang, X. 2019 Urban expansion analysis using Landsat images in Penang, Malaysia. *Sains Malaysiana* **48** (11), 2307–2315.

Tong, S., Li, X., Zhang, J., Bao, Y., Bao, Y., Na, L. & Si, A. 2019 Spatial and temporal variability in extreme temperature and precipitation events in Inner Mongolia (China) during 1960–2017. *Science of The Total Environment* **649**, 75–89.

UN and ASEAN 2019 *Ready for the Dry Years: Building Resilience to Drought in South-East Asia, United Nations Economic and Social Commission for Asia and the Pacific*.

Venkata Rao, G., Venkata Reddy, K., Srinivasan, R., Sridhar, V., Umamahesh, N. V. & Pratap, D. 2020 Spatio-temporal analysis of rainfall extremes in the flood-prone Nagavali and Vamsadhara Basins in eastern India. *Weather and Climate Extremes* **29**, 100265.

Vicente-Serrano, S. M., Beguería, S. & López-Moreno, J. I. 2010 A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *Journal of Climate* **23** (7), 1696–1718.

Wong, C., Liew, J., Yusop, Z., Ismail, T., Venneker, R. & Uhlenbrook, S. 2016 Rainfall characteristics and regionalization in Peninsular Malaysia based on a high resolution gridded data set. *Water* **8** (11), 500.

Xu, K., Yang, D., Yang, H., Li, Z., Qin, Y. & Shen, Y. 2015 Spatio-temporal variation of drought in China during 1961–2012: a climatic perspective. *Journal of Hydrology* **526**, 253–264.

Yang, C. K., Shan, F. P. & Tien, T. L. 2020 Climate change detection in Penang island using deterministic interpolation methods. *Indonesian Journal of Electrical Engineering and Computer Science* **19** (1), 412–419.

First received 27 December 2021; accepted in revised form 4 March 2022. Available online 18 March 2022