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Observed Trends in Extreme Temperature over the Klang Valley, Malaysia

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ABSTRACT

This study investigates the recent extreme temperature trends across 19 stations in the Klang Valley, Malaysia, over the period 2006–16. Fourteen extreme index trends were analyzed using the Mann–Kendall non-parametric test, with Sen's slope as a magnitude estimator. Generally, the annual daily mean temperature, daily mean maximum temperature, and daily mean minimum temperature in the Klang Valley increased significantly, by 0.07°C yr^{-1}, 0.07°C yr^{-1} and 0.08°C yr^{-1}, respectively. For the warm temperature indices, the results indicated a significant upward trend for the annual maximum of maximum temperature, by 0.09°C yr^{-1}, and the annual maximum of minimum temperature, by 0.11°C yr^{-1}. The results for the total number of warm days and warm nights showed significant increasing trends of 5.02 d yr^{-1} and 6.92 d yr^{-1}, respectively. For the cold temperature indices, there were upward trends for the annual minimum of maximum temperature, by 0.09°C yr^{-1}, and the annual minimum of minimum temperature, by 0.03°C yr^{-1}, concurrent with the decreases in the total number cold days (TX10P), with −3.80 d yr^{-1}, and cold nights (TN10P), with −4.33 d yr^{-1}. The 34°C and 37°C summer days results showed significant upward trends of 4.10 d yr^{-1} and 0.25 d yr^{-1}, respectively. Overall, these findings showed upward warming trends in the Klang Valley, with the minimum temperature rate increasing more than that of the maximum temperature, especially in urban areas.

Key words: climate change, extreme temperature, trend, urban environment, tropical area

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Article Highlights:

- Significant warming trends were detected in the Klang Valley, Malaysia.
- The rate of increase in minimum temperature was higher than that of maximum temperature.
- The total number of cold days and cold nights decreased.

1. Introduction

Extreme climates are particularly important elements of climate change because their impacts—especially on the environment and human health—are increasing globally. Temperature is one of the most important variables related to extreme climates and has been studied at global, regional and local scales. Global mean temperatures warmed during the 20th century, which caught the attention of the research community. Based on the Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2013), global average temperature increased by 0.74°C in the last 100 years (1906–2005) and showed a significant increase in more recent times, with a magnitude of 0.15°C (10 yr)$^{-1}$ after 1970. Warming of the global climate has also in-

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creased the intensity and frequency of extreme temperature events, which have in turn resulted in fatalities and serious socioeconomic losses (Easterling et al., 2000; Vincent et al., 2005; Alexander et al., 2006; Lau and Nath, 2012).

Studies on the warming pattern produce results that vary by region, not only because the climate varies regionally but also because of the different methods used to measure temperature extremes (Perkins and Alexander, 2013; Allen et al., 2015; Rohini et al., 2016). According to Hartmann et al. (2013), global and regional changes in climate extremes show an increased number of warm days (TX90P) and nights (TN90P), and a decreased number of cold days (TX10P) and nights (TN10N) over land. On the regional scale over the entire Mediterranean region, researchers have suggested that there has been an increase in warm events with different magnitudes of frequency and duration (Klein Tank and Können, 2003; Kostopoulou and Jones, 2005; Della-Marta et al., 2007; Kuglitsch et al., 2010; Efthymiadis et al., 2011). Dimri et al. (2018) analysed the maximum temperature ($T_{\max}$) and minimum temperature ($T_{\min}$) to determine the possible future changes in temperature over the Himalaya region and reported a significant warming trend with a higher rate of increase for $T_{\max}$ compared to $T_{\min}$. Likewise, many studies have observed extreme climate events for the last few decades across the Asia-Pacific region and indicated similar results. A recent study in China found decreasing trends for cold indices and increasing trends for warm indices in China by using simulations by two regional climate models (RegCM4 and WRF) (Kong et al., 2019). Manton et al. (2001) analyzed 91 stations in 15 countries in Southeast Asia and the South Pacific for extreme temperature and rainfall trends and indicated that the TX90P and TN90P had increased significantly while the TX10P and TN10P had very likely decreased. A study by Choi et al. (2009) found that the TX90P and TN90P had increased compared to TX10P and TN10P, which had decreased in frequency, over the Asia Pacific Network countries during 1955–2007. The recent study by Marjuki et al. (2016) on the variability of the trends in extreme climate indices over Southeast Asia also showed similar results, with an increment in TN90P and strong decline in TN10P. At the country level, there are several studies in the literature regarding temperature and climate in Malaysia. For example, the study by Suhaila and Yusop (2018) on the climate in Malaysia reported that annual and seasonal T_{mean}, $T_{\max}$ and $T_{\min}$ had significantly increased trends, with magnitudes of between 2°C and 5°C $(100\ \text{yr})^{-1}$, based on 30 years of daily temperature data over the Malaysian Peninsula. A recent investigation by Wong et al. (2018) using a gridded dataset at a resolution of 0.05° over a 20-year period indicated significant increasing trends in temperature for both the northeast monsoon (NEM) and southwest monsoon (SWM), with drastic increases in T_{mean} found in the Klang Valley.

Although many studies have analyzed the trends of temperature and climate trends in Malaysia, local information about extreme climate, and especially extreme temperature variables, has received less attention. Some studies have only focused on large spatial extents. For example, Griffiths et al. (2005), who analyzed extreme temperature change in the Asia-Pacific region, included nine stations in Malaysia during 1968–2003 and reported that the increasing trends for $T_{\min}$ were higher compared to those for $T_{\max}$, with statistically significant trends for both. Their study also found that there were significant increases and decreases for the indices of the total number of warm and cool days, respectively. Climate change is expected to have a significant impact on Malaysia in future (Tangang et al., 2012), especially by increasing the temperature year by year. It is necessary to monitor the profile of the extreme temperature series over time as land use changes occur on small spatial scales. Therefore, this study focuses on overcoming these knowledge gaps by observing the extreme temperature trends in detail for specific areas, such as the Klang Valley. A better understanding of trends in local extreme temperature has potential benefits, especially in studies on the effects of extreme temperature on human health in the future.

2. Data and methods

2.1. *Study areas and data collection*

The Klang Valley is located in the central Malaysian Peninsula, encompassing the states of Selangor, Putrajaya and Kuala Lumpur, with an area of 2352 km^2. This area is the most densely populated in Malaysia and surrounded by large-scale industrial and commercial activities. The climate in the Klang Valley is hot and humid throughout the year and affected by the NEM from November until February and by the SWM from May until August. Meanwhile, the inter-monsoon seasons occur from March until April and from September until October, between the NEM and SWM (Syafrina et al., 2015). The SWM is a drier period for the west and north coastal areas of the Malaysian Peninsula, including the Klang Valley. Rainfall in the Klang Valley is estimated to be between 2 and 3 m per year and becomes particularly heavy during the NEM season (Bunnell, 2002). This study was conducted based on the daily maximum temperature ($T_{\max}$, units: °C) and minimum temperature ($T_{\min}$, units: °C) data collected from 19 stations from the Malaysian Meteorological Department (MetMalaysia) (13 stations) and Department of Environment (DOE), Malaysia (six stations), for the period 2006–16. The details and location of the stations, based in urban, suburban and rural areas, are provided in Table A1 in the Appendix and Fig. 1.

2.2. *Preprocessing of data*

Based on previous studies, the preprocessing during this research comprised three steps: (1) data quality control; (2) data homogeneity; and (3) calculation of climate extreme indices.

2.2.1. *Data quality control*

Before the calculation of extreme indices, data quality assessment is an important process to ensure robust results for

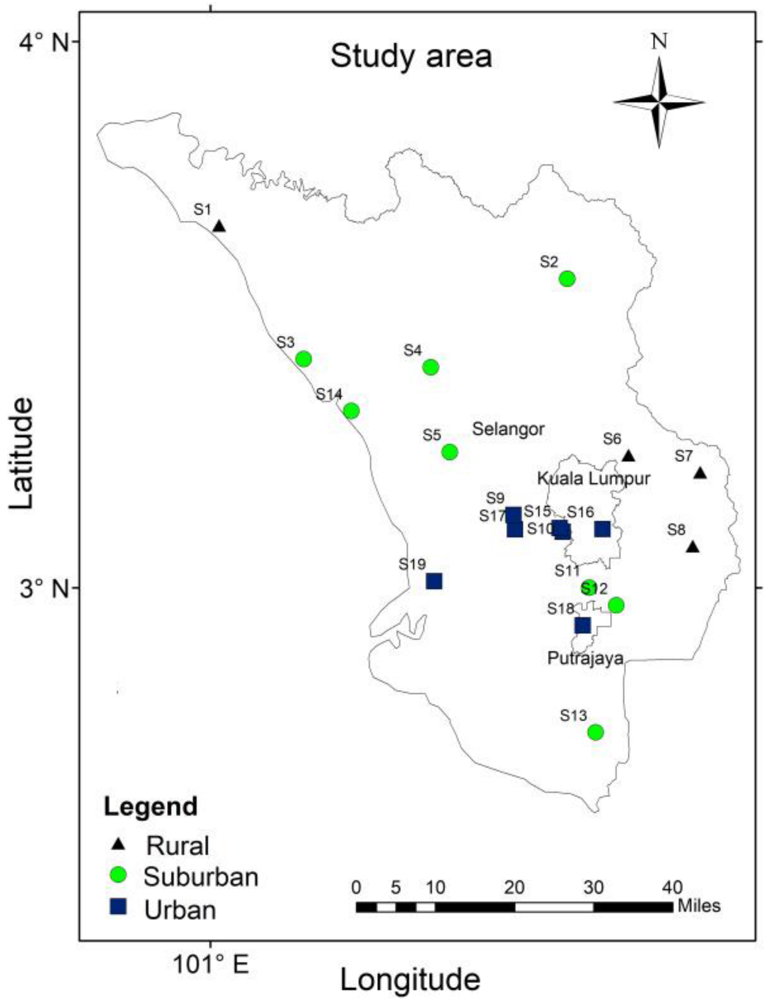


Fig. 1. Locations of the 19 meteorological stations in the Klang Valley area.

trend assessments, since any erroneous outliers can disrupt the trends (You et al., 2008). In this study, RClimDex (R-based program) software was used as a tool to detect missing data, errors and outliers in the daily data series (Zhang and Yang, 2004). The data with any gross errors were excluded for data processing and treated as missing data. For example, if $T_{\max}$ was equal to or less than $T_{\min}$ it was considered a data error for both parameters. Data outliers were detected based on calculation of the exceedance of the interquartile range (IQR) in each month recorded in all observation years, which can potentially identify unrealistic climatic records (Zhang et al., 2005; Stephenson et al., 2014). According to Aguilar and Prohom (2006), any value falling outside the lower and upper IQR bounds can be considered as outliers. Then, the detected outliers are checked to see if the value detected as an outlier really is an outlier. In this case, the outliers were validated against the recorded data from the nearest station. Outlier data were excluded in the calculations of indices and set as missing data. From the results of this process, we noticed that no data errors appeared at any station and less than 5% of the observations at each station were suspected to be outliers in the data. The outliers were checked and more than 95% of these suspected outliers were justified as relating to natural events and were included in the calculation of indices.

2.2.2. *Data homogeneity*

Homogeneity testing is important for identifying abrupt changes and to adjust the observations of the data series. Changes in data series might happen because of climatic shifts (El Niño or La Niña) and non-climatic effects such as resettlement of the sensor, strong environmental changes, and/or the use of different instruments or observing practices (Klein Tank et al., 2009). The changes caused by non-climatic effects need to be identified because they have the potential to affect trend assessment (Aguilar et al., 2003; Trewin, 2013). The RHtestsV4 software (http://etccdi.pacificclimate.org) was used for homogeneity testing of the daily datasets. This software employs a two-phase regression model with a linear trend for the entire series to identify the change points in the time series for each station (Wang, 2003). The results obtained from the test indicated that there were change points in the dataset at around 2009/10 and 2015/16. These changes were probably related to natural climate phenomena, as 2009/10 and 2015/16 were considered among the warmer years in Malaysia over the last decade, caused by El Niño events (MetMalaysia, 2016). Since the change points related to climate phenomena, the data were considered homogenous and still included in the processing of this study.

2.2.3. *Extreme indices*

For this study, only 14 indices relating to temperature were considered, as recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI), as some indices (e.g., indices of frost days and ice days) were not suitable in this study. For the percentiles threshold, we used the 10th and 90th percentiles as thresholds for the calculation of warm and cool index events during the study period (Zhang et al., 2011). For the threshold of the indices, a temperature for summer days (SU) of 34°C was chosen, based on the outdoor human thermal comfort level, which is less than 34°C in the Malaysian region (Makaremi et al., 2012). The extreme hot days index "SU37" was selected based on the heatwave temperature level defined by MetMalaysia (2016). Detailed information on the indices is described on the ETCCDI website (Zhang et al., 2011), as in Table A2 in the Appendix. Before calculation of the indices, the data needed to be checked to fulfil certain requirements, such as no missing values exceeding three days for the calculation of monthly indices, and fewer than 15 days for the calculation of annual indices (Zhang and Yang, 2004). From our observations, we found that less than 0.05% of the observations per station for the daily data did not fulfil the requirements for the calculation of the monthly indices.

2.2.4. *Estimation of trends*

In this study, the Mann–Kendall (MK) test combined with a Sen's slope estimator as a trend magnitude test were used to calculate the trends of extreme temperatures. The MK statistic is a rank-based non-parametric test, which is widely used for climatological and hydrological applications. This method does not need an assumption of a normal distribution and is robust to outliers because the results are not influenced by missing values (Zhang et al., 2005; Vincent et al., 2011; Keggenhoff et al., 2014). The trend results are presented via tables and spatial maps. The confidence level of the trends in this study was 95%.

2.2.5. *Interpolation with GIS*

The software ArcGIS, version 10.3, was used to interpolate the dispersion of extreme temperature indices and visualize the trend patterns at each station. In this study, we chose the Inverse Distance Weight (IDW) method to interpolate the results as it provides a low root-mean-square error value compared to several other techniques (Lu and Wong, 2008). The calculation of IDW is based on Eq. (1), below, where the overall concept is to estimate the unknown value of Y (X_o) at location X_o, given the observed Y value at locations X_i with λ_i are the weights associated with the sampling points X_i.

$$Y(X_o) = \sum\nolimits_{i=0}^{n} \lambda_i Y(X_i)\ .$$

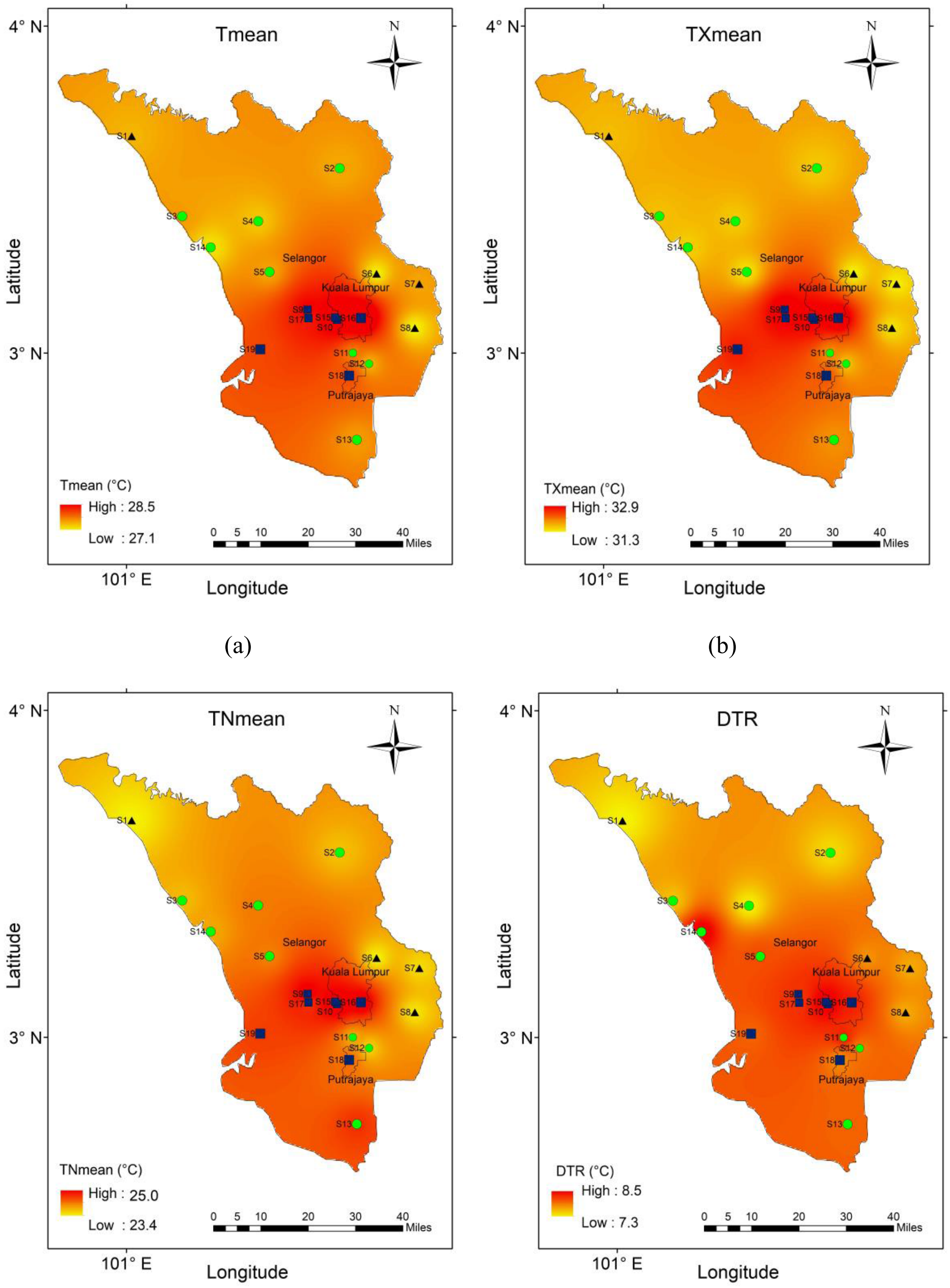
3. Results and discussion

3.1. *Spatial profile of extreme temperature indices across the Klang Valley*

The results of the spatial profile for each of the 14 indices at every station in the Klang Valley during the study

Table 1. Descriptive summary of the distributions of the 14 extreme temperature indices based on the 19 stations.

Station	T_{mean}	TX_{mean}	TN_{mean}	TXx	TNx	TXn	TNn	TX90P	TN90P	TX10P	TN10P	SU34	SU37	DTR
S1	27.3	31.6	23.4	35.8	27.3	23.6	20.3	276	291	391	399	174	0	7.3
S2	27.4	31.5	23.6	36.2	27.2	23.9	20.4	245	220	380	401	132	0	7.4
S3	27.4	31.6	23.7	36.2	27.3	24	20.5	282	306	375	378	194	0	7.5
S4	27.3	31.5	24.0	36.1	27.4	24.2	20.5	290	345	396	384	240	0	7.3
S5	27.4	31.4	24.0	36.6	27.4	24.3	20.6	283	215	364	364	272	0	8.0
S6	27.1	31.3	23.4	36.2	27.1	23.6	20.3	336	350	323	375	290	0	7.7
S7	27.4	31.4	23.5	36.3	27.0	23.6	20.4	327	345	363	383	298	0	7.6
S8	27.1	31.4	23.4	36.2	27.0	23.7	20.3	317	359	369	378	287	0	7.6
S9	28.0	32.7	24.8	37.6	28.3	24.8	21.4	363	374	318	316	631	2	8.1
S10	27.9	32.4	25.0	36.9	29.2	24.8	21.5	389	384	305	310	833	0	8.3
S11	27.5	31.8	23.7	36.7	27.4	23.8	20.5	367	375	339	328	397	0	8.2
S12	27.3	31.5	23.5	36.4	27.3	23.9	20.4	355	377	349	336	419	0	7.8
S13	27.4	31.8	24.4	37.1	27.8	24.1	20.6	370	334	362	325	466	1	7.9
S14	27.2	31.5	23.8	36.1	27.2	23.6	20.4	298	202	329	374	182	0	8.4
S15	28.2	32.8	24.7	37.4	29.5	24.9	21.8	394	397	301	314	825	8	8.5
S16	28.5	32.9	24.9	37.8	29.4	24.9	21.9	389	381	317	320	698	18	8.2
S17	27.8	32.5	24.4	37.3	28.8	24.7	21.5	371	388	306	325	537	5	8.1
S18	27.7	32.1	24.1	36.8	28.7	24.5	21.2	358	367	338	376	368	0	7.7
S19	27.7	32.4	24.3	37.1	28.9	24.8	21.3	338	381	323	330	364	3	7.9

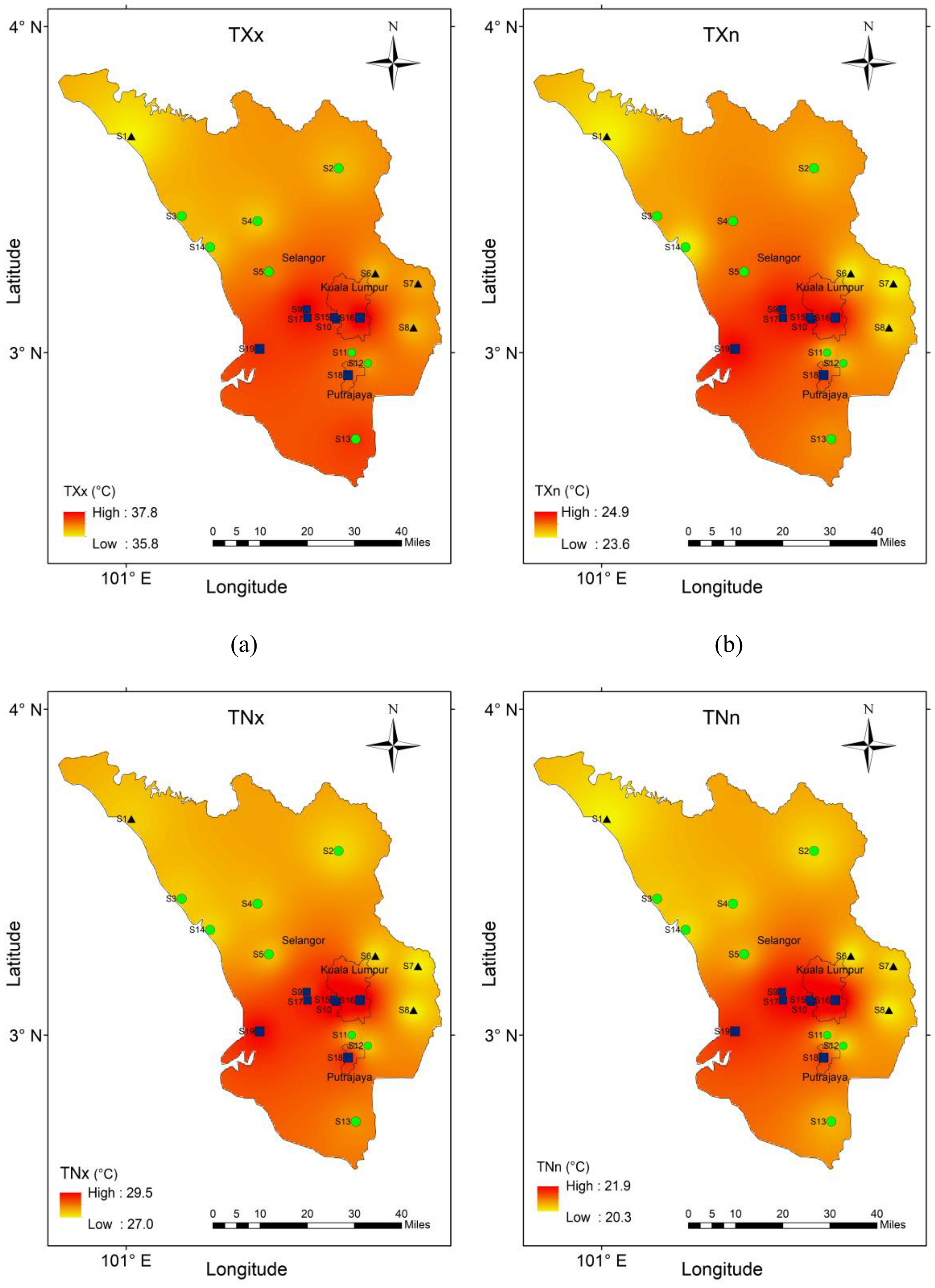


(a) (b)

(c) (d)

Fig. 2. Spatial distribution of the T_{mean}, $\mathrm{TX}_{\mathrm{mean}}$, $\mathrm{TN}_{\mathrm{mean}}$ and DTR indices for the Klang Valley over the last 11 years (2006–16).

period are summarized in Table 1, Fig. 2, Fig. 3 and Fig. 4. As displayed in Fig. 2a, the T_{mean} for the Klang Valley ranged from 27.1°C to 28.5°C. Stations S16 (in the center of the Klang Valley) showed the highest values, while S6 and S8 (east area) had the lowest value. This value is comparable with the general assumption that Malaysia's annual average temperature is between 26°C and 28°C (MetMalaysia, 2016). On average, the mean maximum temperature

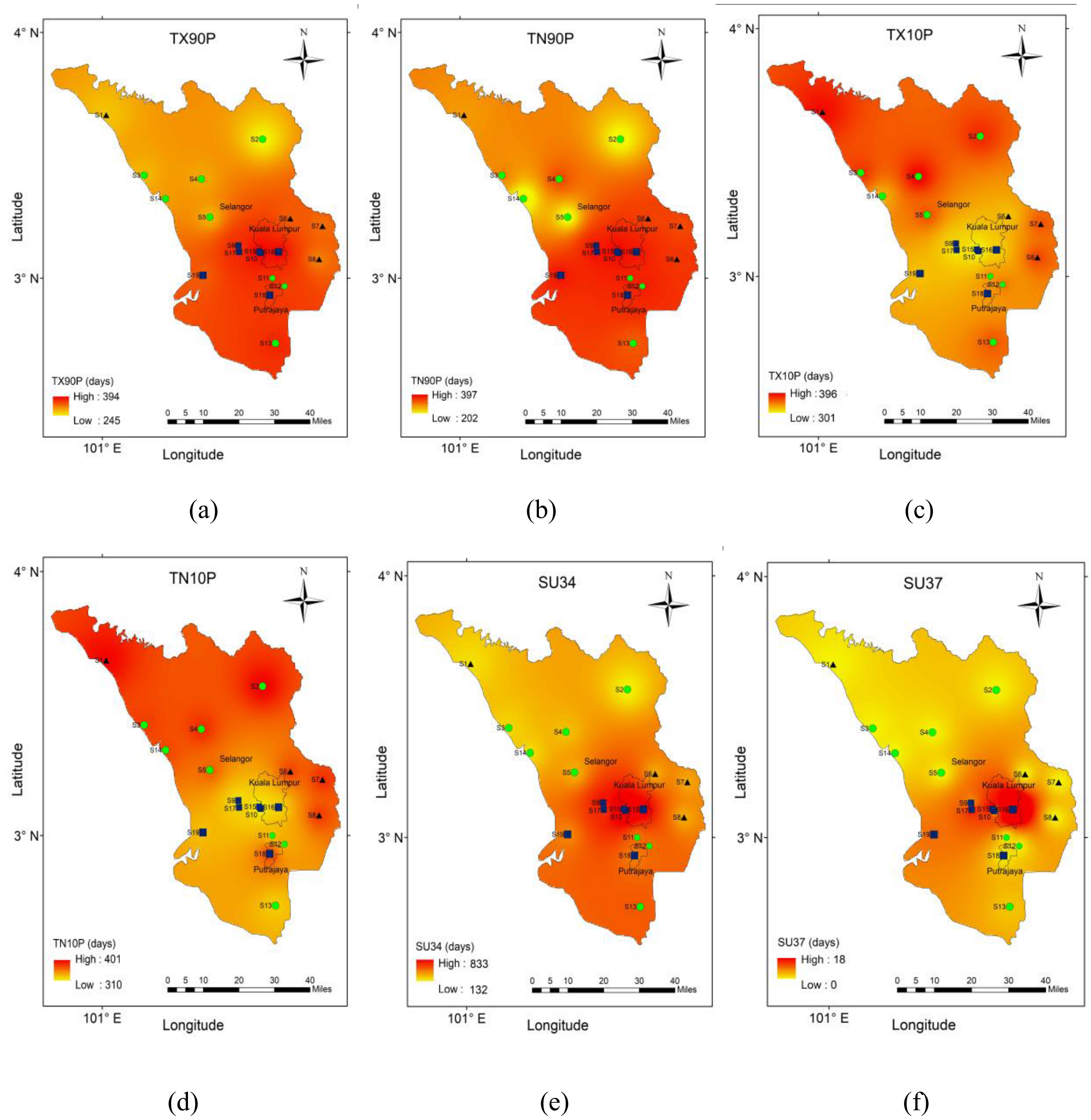


(a) (b)

(c) (d)

Fig. 3. Spatial distribution of extreme temperature indices for the Klang Valley over the last 11 years (2006−16).

(TX_{mean}), mean minimum temperature (TN_{mean}) and diurnal temperature range (DTR) were between 31.3°C and 32.9°C, 23.4°C and 25.0°C, and 7.3°C and 8.5°C, as shown in Figs. 2b−d, respectively. For TX_{mean} and DTR, the highest values were at S16 and S15, both in the central area, while the lowest values for these indices were recorded at S6 and S1, located in the east and northwest area. Meanwhile, for TN_{mean} the highest value was also recorded at S9 (central



(a) (b) (c)

(d) (e) (f)

Fig. 4. Spatial distribution of percentile-based indices for the Klang Valley over the last 11 years (2006–16).

area) and the lowest value at S8 (eastern area). This range was approximately comparable to that presented by Seng (2017) for the Malaysian Peninsula [23°C–24.3°C ($\mathrm{TN_{mean}}$) and 31.8°C–32.7°C ($\mathrm{TX_{mean}}$)]. Overall, the spatial profile for T_{mean}, $\mathrm{TX_{mean}}$ and DTR followed the same pattern in terms of their highest and lowest values during the study period. The similar pattern observed between these indices was possibly due to climatic effects such as increases in cloud cover and increasing anthropogenic emissions (e.g., aerosols) in highly populated urban areas (Karl et al., 1993). We noticed that the highest values for these indices, observed in the central area of the Klang Valley, representing the urban area, resulted from increasing daytime temperatures in conjunction with decreasing nighttime temperatures—a difference that leads to increases in the DTR. However, $\mathrm{TN_{mean}}$ was inconsistent, with the highest values recorded at stations in urban and suburban areas, but also at several stations in rural areas (northern area).

In the case of extreme temperature indices, based on Figs. 3a and b, this study found that S16 and S15 recorded the annual maximum of maximum temperature (TXx) and annual maximum of minimum temperature (TNx) at 37.8°C and 29.5°C, respectively. Meanwhile for the coldest temperatures, the annual minimum of maximum temperature (TXn) was observed at S1, S6 and S7 at 23.6°C, while the annual minimum of minimum temperature (TNn) was detected at S1, S6 and S8 at 20.3°C, as displayed in Figs. 3c and d. The highest warm-temperature values were recorded in the central area, especially in the urban area, compared to stations in the surrounding countryside—an expected result considering that areas with a high density of buildings and urban surfaces usually reveal the highest temperatures (Huang et al., 2008). In addition, high levels of emissions from vehicles may contribute to urban areas being warmer compared to surrounding areas (Bulut et al., 2008). In contrast, for the coldest temperatures, stations located in rural areas showed the coldest values for day and night. One of the factors at play here is that rural areas cool much faster than cities, as winds in rural areas tend to be stronger than in urban areas, providing a cooling effect (Yilmaz et al., 2007), as high buildings can limit air movement (Kuttler et al., 1996). Most of the stations in the urban areas are surrounded by very high buildings, which directly affected the wind values in this study.

For the percentile-based temperature indices, the spatial patterns of TX90P, TN90P, TX10P and TN10P are displayed in Figs. 4a–d. Based on these figures, it can be seen that most of the stations had a total number of days ranging from 200 to 400 during the study period for all the percentile-based temperature indices. There was not much difference in the number of days between stations as the threshold was based on historical recorded data at each station. The spatial profiles show an inconsistent pattern for TX90P and TN90P during the study period. For instance, some stations recorded high numbers of days for TX90P compared to TX90N, and some stations the opposite. By contrast, the spatial profiles show that the total number days for TN10P was consistently higher than TX10P at most stations. This phenomenon may have occurred because of the urban heat island effect combined with increasing anthropogenic emissions in the area. Overall, we can see that total numbers for warm indices were higher than cold indices at most stations in the urban area. Meanwhile, Figs. 4e and f display other temperature indices—the total annual number of summer days that exceed 34°C (SU34) and 37°C (SU37). As the threshold is the same for every station, the results in Fig. 4e show the highest and lowest total days that exceeded 34°C were at stations S10 and S2, with totals of 833 days and 132 days during the study period, respectively. We further found that the stations in the urban areas—notably, the center of the Klang Valley—indicated twice the total number of days exceeding 34°C and 37°C recorded by stations in the suburban and rural areas. Such results explain why people in urban areas are more frequently exposed to temperatures above the thermal comfort level, and this may adversely affect the health of these populations through illness and even death. In the case of summer days (SU37), 7 out of 19 stations recorded days that exceeded 37°C, with S16 recording the highest number at only 18 days. As expected, the relatively higher temperatures happened only at stations located in center of the Klang Valley. Studies on SU37 are particularly useful for observing the occurrence of heat-wave events. In our study area, results indicated that no heat-wave events occurred during the study period, as the number of days exceeding 37°C was statistically insignificant, and on no occasion did this happen for three consecutive days. However, the SU37 index should still be monitored, especially in urban areas, as temperatures increase owing to the global warming phenomenon.

3.2. *Trends of T_{mean}, TX_{mean}, TN_{mean} and DTR*

Table 2 summarizes the trends of the temperature indices for 19 stations across the Klang Valley during 2006–16. All of the stations showed an increasing trend for T_{mean}, TX_{mean} and TN_{mean}. Specifically, 11 of the stations showed a significant increasing trend for T_{mean} and TX_{mean}, and 12 stations for TN_{mean}. Increasing trends could be detected with significant ($p < 0.05$) trends of 0.07°C yr^{-1} for T_{mean} and TX_{mean}, and 0.08°C yr^{-1} for TN_{mean}. The magnitude of increase was higher than previously reported by Seng (2017) for the Malaysian Peninsula [trends of 0.02°C

Table 2. Trends in extreme temperature indices during 2006–16 across the Klang Valley.

Index	Percentage	NSI	NI	NSD	ND	NT	Trend	Average trend
T_{mean}	57.8	11	8	0	0	0	0.02 to 0.15	**0.07**
TX_{mean}	57.8	11	8	0	0	0	0.02 to 0.14	**0.07**
TN_{mean}	73.6	14	5	0	0	0	0.01 to 0.17	**0.08**
DTR	10.5	2	10	0	7	0	−0.06 to 0.05	−0.01
TXx	63.1	12	7	0	0	0	0.00 to 0.19	**0.09**
TNx	47.3	9	8	0	2	0	−0.03 to 0.25	**0.11**
TXn	0.0	0	18	0	1	0	−0.05 to 0.17	0.09
TNn	0.0	0	15	0	4	0	−0.07 to 0.12	0.03
TX90P	57.8	11	8	0	0	0	0.00 to 6.00	**5.02**
TN90P	78.9	15	4	0	0	0	0.00 to 7.20	**6.92**
TX10P	0.0	0	0	4	15	0	−4.10 to -0.30	−3.80
TN10P	0.0	0	0	4	15	0	−5.80 to 0.00	−4.33
SU34	36.8	7	12	0	0	0	0.00 to 9.00	**4.10**
SU37	10.5	2	0	0	0	17	0.20 to 0.50	0.25

Notes: Numbers in bold are significant at the 95% confidence level; the percentage column shows the percentage of stations with significant trends in extreme temperature indices; NSI is the number of stations with significant increasing trends ($p < 0.05$); NI is the number of stations with increasing trends; NSD is the number of stations with significant decreasing trends ($p < 0.05$); ND is the number of stations with decreasing trend; and NT means no trend.

yr^{-1} for T_{mean} and $\mathrm{TX}_{\mathrm{mean}}$, and 0.03°C yr^{-1} for $\mathrm{TN}_{\mathrm{mean}}$]. This might be because our study only focuses on inland regions (the Klang Valley) of the Malaysian Peninsula, where urbanization and industrialization have been growing rapidly for the last two decades. This finding is supported by Wong et al. (2018), in which an abrupt increment of mean temperature (0.06°C yr^{-1}) was found in the Klang Valley and on the west coast of the Malaysian Peninsula during 1995–2006. From Table 2 we can see that the magnitude of $\mathrm{TN}_{\mathrm{mean}}$ is greater than $\mathrm{TX}_{\mathrm{mean}}$, resulting in a decrease in the DTR of about −0.01°C yr^{-1} for the whole area. This sign of decreasing DTR is considered approximately comparable to what was studied by Alexander et al. (2006) and Donat et al. (2013) using gridded data for global assessments. However, the trends at the stations for DTR showed less coherent spatial patterns, with only two (out of the 19) stations with significant trends. Figures 5a–c show the spatial pattern trends at the station level, with increasing trends among the stations from 0.02°C to 0.15°C yr^{-1}, 0.02°C to 0.14°C yr^{-1} and 0.01°C to 0.17°C yr^{-1} for T_{mean}, $\mathrm{TX}_{\mathrm{mean}}$ and $\mathrm{TN}_{\mathrm{mean}}$, respectively. The trends at the station level are more prominent towards the central part of the Klang Valley, with significant upward trends. As expected, the highest increasing trend value was observed in the urban area, especially at stations S9, S10 and S15. One of the contributions to this increasing trend may be the increased urbanization and industrialization that have formed a huge urban complex in the center of the Klang Valley (Hadi et al., 2011). According to Morris et al. (2017), urbanization has a significant effect on the adversity of urban climatological parameters in Greater Kuala Lumpur. In contrast, increasing and decreasing trends of between 0.05°C and −0.06°C yr^{-1} for DTR indices (Fig. 5d) were recorded. S11 and S12 are stations located in the suburban area and were the only stations that presented statistically significant increasing trends for DTR. Despite the fact that the spatial pattern was less coherent, the smaller DTR range between stations proves that the daytime temperature has risen slower than the nighttime temperature. Overall, the results indicate that the indices clearly reflect a significant warming over the whole area during the study period.

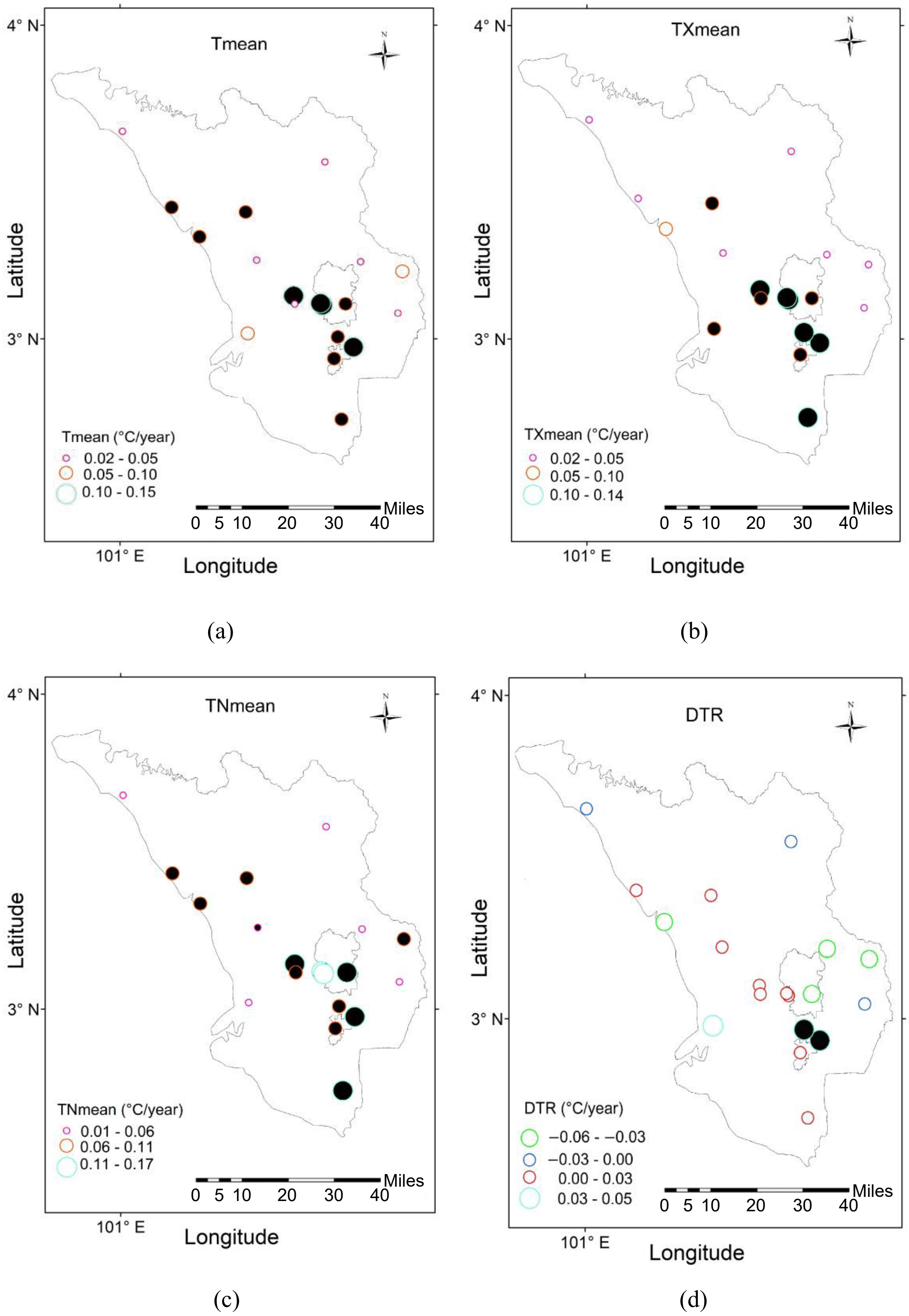
3.3. *Trends in absolute temperature indices*

For the warm extreme indices, TXx showed an increasing trend at almost all stations, with ten of the stations showing statistically significant trends and only two stations showing no trends during the study period. The overall statistically significant trend for TXx was 0.09°C yr^{-1}, and for all stations the trends had rates of increase and decrease of between 0°C and 0.19°C yr^{-1}, as displayed in Fig. 6a. Similarly, strong increasing trends were found for TNx at nearly all stations; just two stations showed a decreasing trend, with nine of the stations showing significant trends. There was an overall statistically significant increasing trend of TNx of 0.11°C yr^{-1}, while the individual station trends were between −0.03°C and 0.25°C yr^{-1} (Fig. 6b). We also noticed a clear warming pattern from the cold extreme indices, as most stations showed increasing trends for TXn and TNn. However, the increasing trends were observed with less and no spatial coherence for TNn and TXn, respectively. For instance, TXn and TNn showed increasing trends for the whole area at 0.09°C yr^{-1} and 0.03°C yr^{-1}, but not significantly, at almost all stations. Figures 6c and d show spatial distribution trends of TXn and TNn at between −0.05°C and 0.17°C, and −0.07°C and 0.12°C yr^{-1}, respectively. From Fig. 6, it is interesting to see different trends between stations in the urban, suburban and rural areas. Significant increasing trends were detected in the central areas consisting of urban and suburban stations, with the average range of 0.07°C–0.25°C yr^{-1} being greater than that of rural areas at −0.03°C–0.06°C yr^{-1}. We can see that warming was more rapid at urban and suburban stations compared to rural stations on average. Over the past few decades, urbanization has expanded rapidly, especially in suburban areas, and may produce an urban heat island effect. Owing to the increase in such activities, urban areas have been expanding rapidly over the last few decades. The rate of urbanization on the Malaysian Peninsula rose from 62% in 2000 to 71% in 2010. The areas of Kuala Lumpur and W. P. Putrajaya showed urbanization levels of 100%, and Selangor showed 91.4% (Department of Statistics Malaysia, 2011). As a result, this process may contribute to the differential of the pattern of warm and cold indices in urban, suburban and rural areas (Burić et al., 2014).

3.4. *Trends in percentile-based temperature indices*

The percentile-based temperature indices (Fig. 7) showed similar trends to those of the extreme temperature indices. For the warm indices, both TX90P and TN90P showed significant increasing trends, with overall trends of 5.02 and 6.92 d yr^{-1}, respectively. This result indicates that the nighttime warming was higher than the daytime warming during the study period. All stations showed an increasing trend, and approximately 57.8% of the stations had statistically significant trends for TX90P, with the rate of increase ranging from 0 to 6.00 d yr^{-1}, as shown in Fig. 7a. Similarly, for TN90P, all stations showed an increasing trend, with 73.7% showing statistically significant trends. Figure 7b shows the individual station trends for TN90P, which had trend magnitudes ranging between 0.00 and 7.20 d yr^{-1}. The signs of increasing trends seen in this study are similar to the findings of Griffiths et al. (2005) for the Malaysian Peninsula, but the rate of increase is slightly higher compared to what they estimated (0.0–0.9 d yr^{-1} for TX90P and 0.9–2.2 d yr^{-1} for TN90P). This may due to the small scale of the study area and the differences in the study period, as their study used data spanning 1987–2005, compared to 2006–16 used in our study. Meanwhile, for TX10P and TN10P, all stations showed a decreasing trend, with only 21.1% and 26.3% showing statistical significance for the indices, respectively. A decreasing trend was observed during the study period, with overall trends of −3.80 and −4.33 d yr^{-1}, and the station by station trends ranged from −4.11 to −0.30 d yr^{-1}

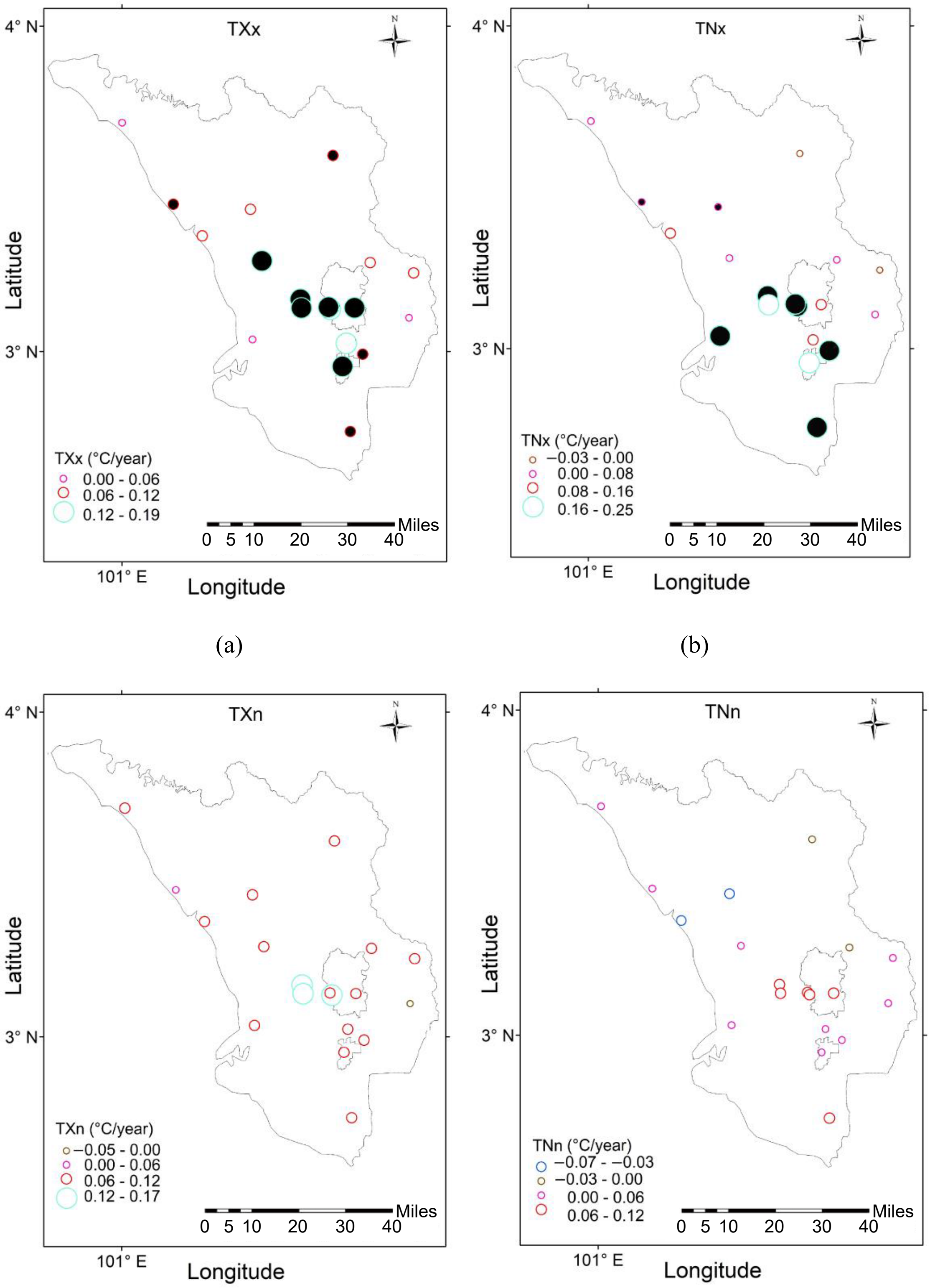
(Fig. 7c) and −5.80 to 0 d yr^{-1} (Fig. 7d) for TX10P and TN10P, respectively. However, compared to the findings of Griffiths et al. (2005), our results show higher decreasing rates (−0.09 to −0.05 d yr^{-1} for TX10P and −0.1 to −0.09 d yr^{-1} for TN10P). Consistent with the upward trends presented for TXx, TNx, TXn and TNn, the percentile-based in-



(a) (b)

(c) (d)

Fig. 5. Spatial trends of T_{mean}, $\mathrm{TX}_{\mathrm{mean}}$, $\mathrm{TN}_{\mathrm{mean}}$ and DTR for the Klang Valley over the last 11 years (2006–16). Black circles show significant trends ($p < 0.05$).

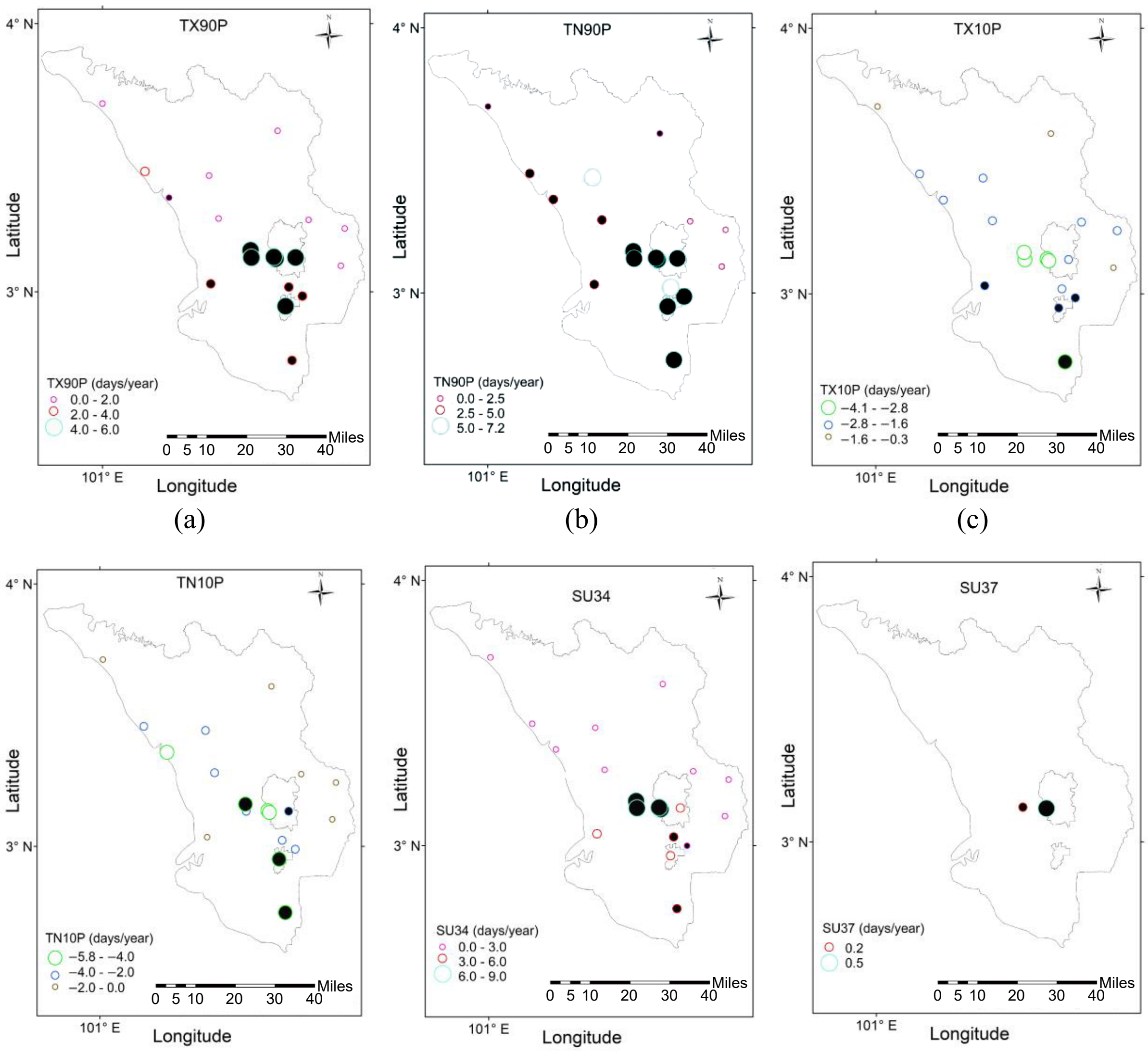


(a) (b)

(c) (d)

Fig. 6. Spatial trends of extreme temperature indices for the Klang Valley over the last 11 years (2006–16). Black circles show significant trends ($p < 0.05$).

dices indicate that the total number of days for the warm indices clearly increased, and the cold indices decreased, over the last few decades. In general, the variations of TN10p and TN90p were found to be higher than those of TX10p and TX90p, and this is comparable with the previous global assessment by Donat et al. (2013). This clearly showed that



(a) (b) (c)

(d) (e) (f)

Fig. 7. Spatial trends of percentile-based indices for the Klang Valley over the last 11 years (2006–16). Black circles show significant trends ($p < 0.05$).

the Klang Valley area became warmer, especially during the night compared to the daytime, and this sign is consistent with the expected results in terms of global climate warming. Meanwhile, SU34 recorded a significant increasing trend, at 4.10 d yr^{-1} for the whole area. All stations in the study area experienced increasing trends, with 36.8% being significant. The trends for all stations were between 0 and 9.00 d yr^{-1} during the last few decades (Fig. 7e). However, in contrast, only two stations showed statistically significant trends for SU37, at 0.20 and 0.50 d yr^{-1}, as displayed in Fig. 7f. The central area showed the highest magnitude of trends for SU34 and SU37.

Overall, the results in this study show similar patterns to those reported by Tan et al. (2019) for the northwestern Malaysian Peninsula, where warm indices, such as TXmean, TNmean, TX90P and TN90P, showed significant increasing trends, whereas cold indices showed significant decreasing trends for TX10p and TN10p. The warming rate of TNmean was higher than TXmean, indicated by the decreasing trend for DTR at a rate of 0.01°C yr^{-1} for the Klang Valley area. This may happen because of the urban heat island and climatic effects, as an increase in cloud cover may indirectly increase greenhouse gas and aerosol concentrations (Karl et al., 1993). The decreasing trend of DTR is consistent with other studies by Amirabadizadeh et al. (2015) and Suhaila and Yusop (2018).

4. Conclusions

This study investigated the trends of extreme temperature over the Klang Valley area using daily temperature datasets from 19 meteorological observatories for the past decade (2006–16). The results suggest that almost all the warm indices showed increasing trends compared to the cold indices. Out of 14 indices, eight showed statistically significant increasing trends. Generally, over the Klang Valley, the

T_{mean}, TX_{mean} and TN_{mean} indicated significant warming trends of 0.07, 0.07 and 0.08°C yr^{-1}, respectively. Also, most of the warm indices (TXx, TNx, TX90P, TN90P and SU34) were found to have significant increasing trends, at 0.09°C yr^{-1}, 0.11°C yr^{-1}, 5.02 d yr^{-1}, 6.92 d yr^{-1} and 4.10 d yr^{-1}, respectively. On the other hand, the cold indices of TNx and TNn were observed to have increasing trends of 0.09 and 0.03°C yr^{-1}, and there were decreasing trends for TX10P and TN10P of −3.80 d yr^{-1} and −4.33 d yr^{-1}, respectively. Other indices, such as DTR, showed a decreasing trend (−0.01°C yr^{-1}), and for SU37 there was an increasing trend of 0.25 d yr^{-1}. Overall, this study indicates that the warming trend and minimum temperature extremes for the whole area are stronger than the maximum temperature extremes, consistent with previous global and regional studies. In this study, there were more statistically significant trends for warm events than for cold events, indicating an apparent shift towards warmer conditions during the study period. Meanwhile, the spatial pattern of trend magnitude showed that the central area, comprising mostly urban stations, depicted stronger magnitudes compared to suburban and rural stations for the warm indices, especially TXx, TNx and SU34. Most stations in urban areas showed increasing trends for all indices except TX10P and TN10P.

However, this study has some limitations, as the trends were analyzed using short-term time series data (2006–16). The use of short-term data may also have affected the results whereby several indices showed higher trends compared to other studies. The trend analysis was also carried out on an annual basis only, for the whole area and station by station. Another important limitation of this work is the comparison of the effect of urban, suburban and rural stations on extreme temperatures using only the trend magnitude. The calculation of urbanization effects may provide some information on the contribution of urbanization affecting extreme temperature trends. Since the urban heat island effect due to urbanization may cause the spatial difference in the warm and cold pattern, information in the form of data related to urbanization in the urban area is very important for future studies. Data such as these, in combination with regional climate models, would be more meaningful in establishing future projections for impact assessments of extreme temperature. Future studies should take into account seasonal scales with other parameters, such as precipitation. Studies on the variations in temperature extremes during the recent warming hiatus are also of great significance for understanding climate change in Malaysia.

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Appendix

The meteorological data were obtained from 19 air monitoring stations in the Klang Valley (Table A1). Seven stations (S9, S10, S15, S16, S17, S18, S19) represent the urban areas in the middle and west areas of the Klang Valley. This area is heavily developed, particularly with commercial and residential areas. Meanwhile, eight stations (S2, S3, S4, S5, S12, S13, S14, S15) are located in well-developed suburban towns in the Klang Valley, composed predominantly of high-density residential, industrial and commercial areas,

Table A1. List of the meteorological stations, including their geographical coordinates in decimals, for the Klang Valley.

Station no.	Name	Longitude (°E)	Latitude (°N)	Description
S1	Pusat Pertanian Sungai Besar, Sabak Bernam	101.0160	3.6637	Rural
S2	Hospital Kuala Kubu Bharu	101.6528	3.5653	Suburban
S3	Pusat Latihan Kejuruteraan Pertanian, Tanjung Karang	101.1706	3.4184	Suburban
S4	Sime Darby Ladang Tennamaram, Bestari Jaya	101.4035	3.4032	Suburban
S5	Sime Darby Plantation, Sungai Buloh	101.4380	3.2482	Suburban
S6	Klang Gates Dam	101.7652	3.2430	Rural
S7	Semenyih Dam	101.8964	3.2119	Rural
S8	Hulu Langat Dam	101.8824	3.0769	Rural
S9	MMD Subang	101.5544	3.1328	Urban
S10	MMD Petaling Jaya	101.6449	3.1022	Urban
S11	Institut Latihan Pengembangan Pertanian, Serdang	101.6931	3.0000	Suburban
S12	PORIM, Bangi	101.7425	2.9674	Suburban
S13	KLIA, Sepang	101.7051	2.7347	Suburban
S14	Sekolah Menengah Sains, Kuala Selangor	101.2581	3.3234	Suburban
S15	Sekolah Rendah Sri Petaling, Petaling Jaya	101.6391	3.1089	Urban
S16	SMK Seri Permaisuri, Cheras	101.7177	3.1070	Urban
S17	Sekolah Kebangsaan TTDI Jaya, Shah Alam	101.5573	3.1066	Urban
S18	Sekolah Kebangsaan Putrajaya Presint 8(2), Putrajaya	101.6815	2.9308	Urban
S19	SMK Raja Perempuan Zarina, Klang	101.4098	3.0116	Urban

such as hotels shopping malls, and restaurants. The remaining stations (S1, S6, S7, S8) represent the rural area in the north and south of the Klang Valley. Some of the stations (S6, S7, S8) are surrounded by forest and have very limited human activity. The urban, suburban and rural areas were classified based on population, non-agricultural activities and the development of the areas. Detailed descriptions of the stations are given in Table A1.

A total of 14 temperature indices were considered in this study. The indices were characterized based on intensity and frequency of extremes. Some of the indices are based on fix thresholds where the thresholds are the same for all stations for example SU34 and SU37. Other indices are based on thresholds that vary from location to location where the indices are computed based on percentile at each station. Detailed information on the indices is described on the ETCCDI website (Zhang et al., 2011) and presented in Table A2.

Table A2. Definitions of the ETCCDI extreme indices used in this study.

Abbreviation	Index Name	Definition	Unit
T_{mean}	T_{mean}	Annual mean temperature	°C
$\mathrm{TX}_{\mathrm{mean}}$	Mean $T_{\max}$	Annual mean of $T_{\max}$	°C
$\mathrm{TN}_{\mathrm{mean}}$	Mean $T_{\min}$	Annual mean of $T_{\min}$	°C
DTR	Diurnal temperature range	Annual mean difference between daily $T_{\max}$ and $T_{\min}$	°C
TXx	Max $T_{\max}$	The highest value of daily maximum temperature	°C
TNx	Max $T_{\min}$	The highest value of daily minimum temperature	°C
TXn	Min $T_{\max}$	The lowest value of daily maximum temperature	°C
TNn	Min $T_{\min}$	The lowest value of daily minimum temperature	°C
TN10P	Number of days with cold nights	Number of days with minimum temperature < 10th percentile	days
TX10P	Number of cold days	Number of days with maximum temperature < 10th percentile	days
TN90P	Number of days with warm nights	Number of days with annual minimum temperature > 90th percentile	days
TX90P	Number of warm days	Number of days with annual maximum temperature > 90th percentile	days
SU34	Number of summer days	Number of days exceeding maximum temperature > 34°C	days
SU37	Number of heat days	Number of days exceeding maximum temperature > 37°C	days

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