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Temporal and Spatial Evaluations of Extreme Rainfall Relationship with Daily Surface Air Temperature in Peninsular Malaysia

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Abstract— **Extreme rainfall is expected to increase as the climate warms, with the rate of increase at 7% per degree of warming following the Clausius-Clapeyron (CC) relationship. However, studies showed that the rate of increase might not necessarily follow the relationship. This study investigates temporal and spatial variations of daily rainfall relationship with surface air temperature in Peninsular Malaysia using data from the Global Historical Climatology Network (GHCN) using a fixed temperature interval binning method and quantile regression method. Investigation reveals that a negative scaling of daily extreme rainfall was observed for all surface air temperature and percentiles investigated, in contrast with the expectations from the CC relationship. The largest seasonal variation at 99th percentile was observed in December-January (DJF), while the lowest scaling rate was in March-May (MAM). The scaling rate tends to be higher in Subang and Melaka, and lower in Bayan Lepas, Kota Bharu and Kuantan. The scaling rate also tends to be stronger at 99th percentile compared to the lower rainfall events at 95th and 75th percentile and in warmer seasons compared to colder seasons. Further, the results show that the intensity of daily extreme rainfall in Peninsular Malaysia is decreasing with increasing surface air temperature.**

Keywords— **Extreme rainfall; Clausius-Clapeyron relation; trend analysis; Southeast Asia; Peninsular Malaysia.**

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I. INTRODUCTION

Intergovernmental Panel on Climate Change (IPCC) in their latest report [1] used the word 'unequivocal' to state that climate change was happening and highlighted the increasing trend of heavy precipitations over many regions due to the changing climate [2]. The sign of changing climate was also detected at the local climate, where there is evidence of an increase in temperature in Peninsular Malaysia in recent years [3]. Thus, it is expected that the increasing trend as reported in IPCC will be detected in Peninsular Malaysia and indeed has been reported in various studies [4]–[6].

Westra *et al.* [2] review the current outlook on extreme rainfall highlights the increasing magnitude and frequency of extreme daily rainfall over most continents. Further, the review also noted a link between anthropogenic climate change and the increase in extreme weather events, which may lead to more severe or frequent flooding [6]. However, with a lack of observational studies on changes in rainfall patterns and intensities with a warming trend [7], there is an interest to establish the relationship between rainfall and temperature [8]. The physical basis behind the motivation is based on the Clausius-Clapeyron (CC) relationship.

The CC relationship governs how moisture holds in the atmosphere. Using this relationship, Trenberth *et al.* [9] argued that when the intensity of extreme rainfall changes faster than the evaporation rates, the intensity should eventually balance the converging moisture. Thus, Trenberth *et al.* [9] theorize that the intensity of extreme rainfall will change at the same rate as the moisture-holding capacity in the atmosphere. If the rainfall dynamics remain constant, for example, rainfall efficiency or vertical updraft velocities [10], extreme rainfall is expected to increase at the rate of 7% per degree of warming as per expectation from the of CC relationship [11].

Herath *et al.* [12] noted Lenderink and van Meijgaard [13] to be among the first to investigate the relationship between rainfall and temperature. In their study, Lenderink and van Meijgaard [13] used the temperature binning method to find the relationship, where the rainfalls were binned into bins of equal temperature interval. Since then, the technique by

Lenderink and van Meijgaard [13] has been used in many studies in different parts of the world to investigate the relationship of rainfalls with temperature. The studies show that observational data and modeling largely support the CC scaling hypothesis at the local and global scale [14], [15]. However, the studies also revealed uncertainties around the extend of intensification at the temporal scale. At the sub-daily level, extreme rainfall is found to be increasing at the rate as large as 14% per degree of warming as observed in the Netherlands, Japan, and Hong Kong [14]–[16]; while in northern Australia, a decreasing trend of intensification is observed [17]. The extend of intensification also found to be spatially diverse with global analysis on daily extreme rainfall shows the positive scaling rate at higher latitudes while at tropics, a negative trend was observed [14].

While many studies have been done in mid-latitude, such study lacks the regions that experience high surface air temperature, such as in tropics, especially in Southeast Asia [2]. The study in Brazil [18] and Darwin, Australia [12] has shown that the rainfall-temperature relationship at higher temperatures will depart from the CC scaling hypothesis. The moisture availability at higher temperatures might play a part in the negative scaling observed in the study. Therefore, this study aims to complement the study on the rainfall-temperature relationship in the tropics [18] and Herath *et al.* [12] investigating the daily rainfall relationship with surface air temperature in Peninsular Malaysia using observations data from the Global Historical Climatology Network (GHCN). This study investigates the rainfall relationship with temperature for different time slices and whether moisture availability plays a part in the rainfall-temperature relationship**.**

II. MATERIALS AND METHODS

A. *Site Location*

Peninsular Malaysia is located in Southeast Asia which features a high surface air temperature with a very humid climate. The average annual mean surface temperature in Peninsular Malaysia is around 26-28°C, whereas the average daily humidity is around 42-70% with average daily maximum humidity greater than 94% [19]. Rainfalls in Peninsular Malaysia are generally convective, localized, and very intense. The diurnal cycle of the rainfall features early morning primary peak and late evening secondary high rainfalls over the coastal area, while over inland area rainfalls peaked in the afternoon [20].

Seasonal variations of rainfalls in Peninsular Malaysia are mainly attributed to the two main seasons: Northeast Monsoon Season (NEM) and Southwest Monsoon Season (SEM) [6]. NEM generally starts from November until March during which winds from Mainland China blow towards the South China Sea before passing into Peninsular Malaysia. NEM features strong winds accompanied by approximately four or five monsoon surges. SEM, on the other hand generally starts from May until September during which winds from the Australian continent blows towards Sumatera before going into Peninsular Malaysia.

Rainfall is generally more intense during NEM, particularly on the eastern part of Peninsular Malaysia, due to the sheltering effect of the mountain range located inland, which renders the western area from receiving rain [5]. On the other hand, SEM features a drier condition for the whole region, particularly on the western part of Peninsular Malaysia [5]. A transition period between the two monsoons is marked with weaker and unstable winds blowing at all directions [19] during which rainfalls are generally intense in the form of convective rains [5], [21].

B. *Data Acquisitions*

For this study, five weather stations in Peninsular Malaysia were chosen from the GHCN to provide observational rainfall and surface air temperature data at daily timescale. GHCN is an integrated database that summarizes daily climatological data for more than 100,000 land surface stations in 180 countries maintained by National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI). All sites used in this study have at least 20-years of daily rainfall and surface air temperature data, with data loss of less than 30% [8], [22]. The high threshold requirement for the datasets is crucial to ensure a significant number of rainfall-temperature data pairs available for analysis. The study is focused on the period between 1974 and 2018, corresponding to 225 observational years of data. Fig. 1 shows the location of weather stations used in this study. Table 1 summarizes the basic information related to the weather stations used in this study.

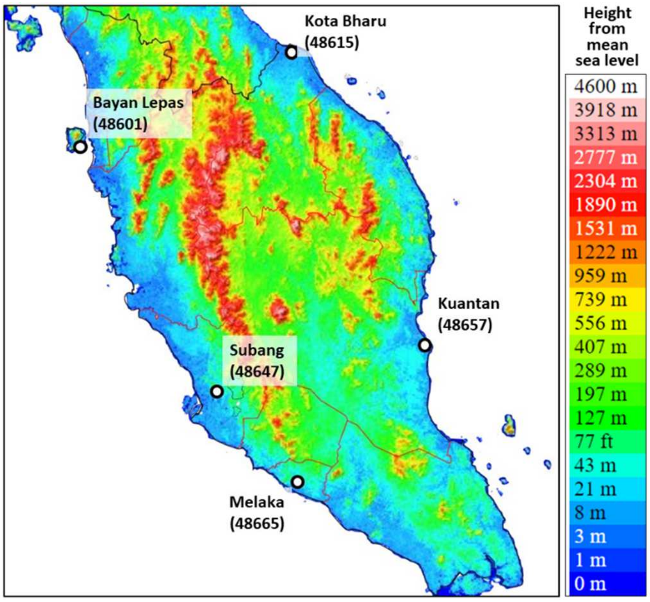

Fig. 1 The topographic map of Peninsular Malaysia showing the location of the weather stations used in this study

TABLE I
RELATED INFORMATION ON THE FIVE WEATHER STATIONS IN FIG. 1

Location	WMO Station Identifier	Latitude (°N)	Longitude (°E)
Bayan Lepas	48601	5.29694	100.27222
Kota Bharu	48615	6.16361	102.30056
Kuantan	48657	3.77222	103.21194
Melaka	48665	2.26667	102.25000
Subang	48647	3.13056	101.55250

C. *Methodology*

This study applied the methodology proposed by Hardwick Jones, Westra, and Sharma [22] to evaluate the relationship between daily rainfall intensity and daily mean surface temperature for the whole study period and at seasonal timescale. This method has been used extensively in many studies, for example, in the Mediterranean [10], Brazil [18], and Japan [23]. Using this approach, the daily rainfall with a depth of more than 0.1 mm was paired with the corresponding daily mean surface of air temperature. The rainfall-temperature pairs were then placed equally into 10 bins. To ensure the bins are statistically significant for analysis, a minimum number of samples of at least 100 rainfall-temperature pairs in each bin was required following [10].

In each bin, rainfalls were ranked according to depth to determine the 75th, 95th, and 99th percentile, where for example, 99th corresponds to the top one percent of the rainfall depth distribution of the bin [8], [12], [24], [25]. The relationship of extreme rainfall with mean surface temperature was obtained by fitting a least-squares linear regression of the logarithms of the percentile rainfall depth against the mean temperature of the respective bin. The linear progression function `lm` in the R program (http://www.r-project.org) was used to fit the regression.

Following Hardwick Jones, Westra, and Sharma [22], the relationship of rainfall, P, with temperature difference ΔT is given by

$$P_2 = P_1(1+\alpha)^{\Delta T} \tag{1}$$

where P_1 and P_2 are the rainfall depth at temperature T_1 and T_2 respectively (hence $\Delta T = T_2 - T_1$); and α is the rainfall-temperature scaling coefficient.

In addition to the binning approach, this study employed another approach called quantile regression. Quantile regression differs from the binning approach, where the rainfall-temperature scaling is estimated directly. Hence no binning is required. Using this approach, rainfalls were plotted against temperature, where the quantile regression is applied to the logarithm of rainfall depth following Wasko and Sharma [8]. The relationship of P with T was then obtained from

$$\ln P = \beta_0^q + \beta_1^q T \tag{2}$$

where $0 < q < 1$ is the quantile. The value of α is determined from β_1^q term, such that

$$\alpha = \Delta P/\Delta T = 100(e^{\beta_1} - 1) \tag{3}$$

following Schroeer and Kirchengast [26]. When $\alpha = 0.0725$, it is equivalent to a CC-like scaling of 7.25 % ◦C^{-1}.

III. RESULTS AND DISCUSSION

Fig. 2 shows the 99th percentile of rainfall depth as a function of daily mean temperature. For comparison, 75th and 95th percentiles are also shown in Fig. 2. Since the rainfall-temperature pairs were placed into bins equally, the temperature interval which was represented by the mean temperature of the bins, varies from one bin to another. A wider temperature interval was observed at the very low and high temperature, which implies a small number of rainfall-temperature pairs at the very low and high mean surface air temperature. Physical inspection of Fig. 2 indicates that the exponential model derived from Equation (1) is suitable for the fit. Thus the value of α from the regression model can be used to represent the scaling of extreme rainfall with temperature in Peninsular Malaysia. Table 2 summarizes the value of α computed from the regression fit in Fig. 2. From Table 2, a negative relation between rainfall extremes and the surface air temperature was observed regardless of the percentile used in contrast to what would be expected from the CC relationship. The negative trend observed here implies that an increase in temperature could decrease daily rainfall intensity.

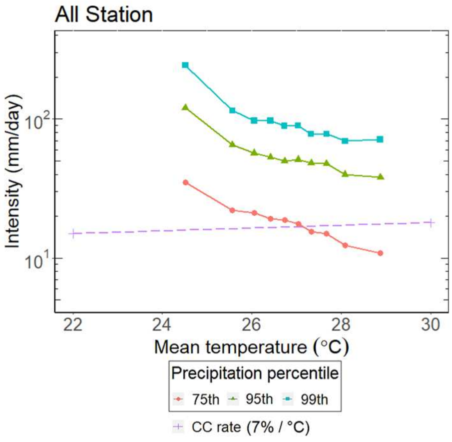

Fig. 2 The relationship of 75th (red), 95th (green), and 99th (blue) percentile daily rainfall intensity with mean surface air temperature for the period from 1974 to 2018 computed from observations at all weather stations in the study. The dashed purple line indicates CC scaling of 7 % ◦C^{-1}

TABLE II
SUMMARY OF EXPONENTIAL REGRESSION FROM FIG. 2

Percentile	α	Standard Error	p-value
99	−0.226	0.046	< 0.01
95	−0.208	0.035	< 0.01
75	−0.224	0.015	< 0.01

The analysis in Fig. 2 was repeated to investigate whether the trend of rainfall with surface air temperature in Peninsular Malaysia is different spatially and temporally throughout the year. Fig. 3 shows variation by location of the relationship of 50th, 65th, 75th, 85th, 95th and 99th percentile of rainfall depth as a function of daily mean temperature while Fig. 4 shows the monthly variations of the relationship at 75th, 95th and 99th percentile of rainfall depth.

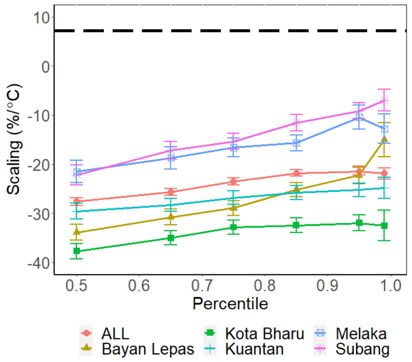

Fig. 3 The scaling by location of 50th, 65th, 75th, 85th, 95th, and 99th percentile of precipitation depth as a function of daily mean temperature for the period from 1974 to 2018 calculated using quantile regression approach. The whiskers show standard error in scaling for the percentile. The dashed black line indicates CC scaling of 7 % ◦C^{-1}

Both Fig. 3 and Fig. 4 were computed using Equation (2) and Equation (3) to present the relationship of rainfall with temperature. Fig. 3 and Fig. 4 reveal that the negative trend of daily extreme rainfall relationship with surface air temperature computed for the whole time series shown in Fig. 2 was also observed at all weather stations and throughout the year.

Looking at Fig. 3, the scaling of extreme rainfall with the surface air temperature at weather stations shows a similar negative trend observed in Fig. 2. The scaling of rainfall with surface air temperature appears to increase as analysis moving towards the extremes. However, no weather stations observed scaling in line with the CC scaling value of 7% °C-1; where all weather stations in the study observed scaling in the negative range. Variations did show when an individual weather station was considered. Subang and Melaka, located on the west coast of Peninsular Malaysia, observed a higher scaling rate above the scaling rate when rainfall relationship with surface air temperature from all weather stations is considered. Bayan Lepas in the northern part of Peninsular Malaysia, and Kota Bharu and Kuantan in the east coast, on the other hand, observed scaling rate below the all-weather stations scaling rate, with the exception in Bayan Lepas at 99th percentile, where the scaling rate appears to increase faster than the all-weather scaling rate.

Looking at Fig. 4, the scaling of extreme rainfall with surface air temperature from Month 1 (January) to Month 3 (March) and from Month 11 (November) to Month 12 (December) appears to be stable for all quantiles investigated. From Month 4 (April) to Month 10 (October), the scaling at all percentiles deviates from each other, with the largest deviation of the scaling between the 75th and 99th percentile occurs in Month 7 (July) and Month 9 (September). Similar to Fig. 3, regardless of the variations from month to month, the scaling of rainfall with surface air temperature appears to increase as analysis moving towards the extremes, although still in the negative scaling trend. The results presented in Fig. 2, Fig. 3, and Fig. 4 agree with the previous study by Herath *et al.* [12] where extreme rainfalls are highly responsive with temperature compared to the average rainfalls.

Furthermore, results shown in Fig. 4 was also observed when seasonality is considered according to results shown in Fig. 5. Fig. 5 shows the seasonal variation of the 75th, 95th, and 99th percentile of rainfall depth as a function of daily mean surface air temperature for December-February (DJF), March-May (MAM), June-August (JJA) and September-November (SON). Again, a physical inspection of Fig. 5 indicates that the exponential model derived from Equation (1) is suitable for the fit, thus the value of α from the regression model can be used to represent the scaling of extreme rainfall with temperature for DJF, MAM, JJA and SON in Peninsular Malaysia. Fig. 5 reveals that the negative trend of daily extreme rainfall relationship with surface air temperature computed for the whole time series as shown in Fig. 2 was also observed at all seasons investigated.

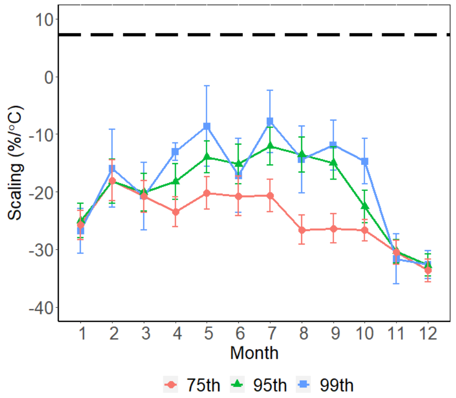

Fig. 4 Monthly variations of the scaling of 75th (red), 95th (green) and 99th (blue) percentile daily rainfall intensity with mean surface air temperature for the period from 1974 to 2018. The whiskers show standard error in scaling for the month. The dashed black line indicates CC scaling of 7 % °C^{-1}

Table 3 summaries the value of α computed from the regression fit in Fig. 5.

TABLE III

SUMMARY OF EXPONENTIAL REGRESSION FROM FIG. 5

Month	Percentile	α	Standard Error	p-value
DJF	99	−0.281	0.039	< 0.01
	95	−0.287	0.037	< 0.01
	75	−0.270	0.052	< 0.01
MAM	99	−0.129	0.030	< 0.01
	95	−0.158	0.011	< 0.01
	75	−0.193	0.013	< 0.01
JJA	99	−0.148	0.041	< 0.01
	95	−0.132	0.017	< 0.01
	75	−0.232	0.026	< 0.01
SON	99	−0.242	0.048	< 0.01
	95	−0.242	0.029	< 0.01
	75	−0.260	0.026	< 0.01

Further, Fig. 5 reveals that the scaling of extreme rainfall with surface air temperature varies with the seasons. The scaling of extreme rainfall with surface air temperature during DJF and SON appears to decrease at much large rate compared to the scaling during MAM and JJA. In terms of the intensity of rainfall, DJF and SON experience higher rainfall intensity compared to MAM and JJA, coincides with the monsoon seasons in Peninsular Malaysia. Relating the results to the monsoon seasons, the scaling of extreme rainfall with surface air temperature during NEM was decreasing faster than during SEM. With higher temperature range during MAM and JJA compared to DJF and SON, results presented in Fig. 5 implies that the scaling of extreme rainfall with temperature was increasing in a warmer climate, similar to the results in Fig. 4.

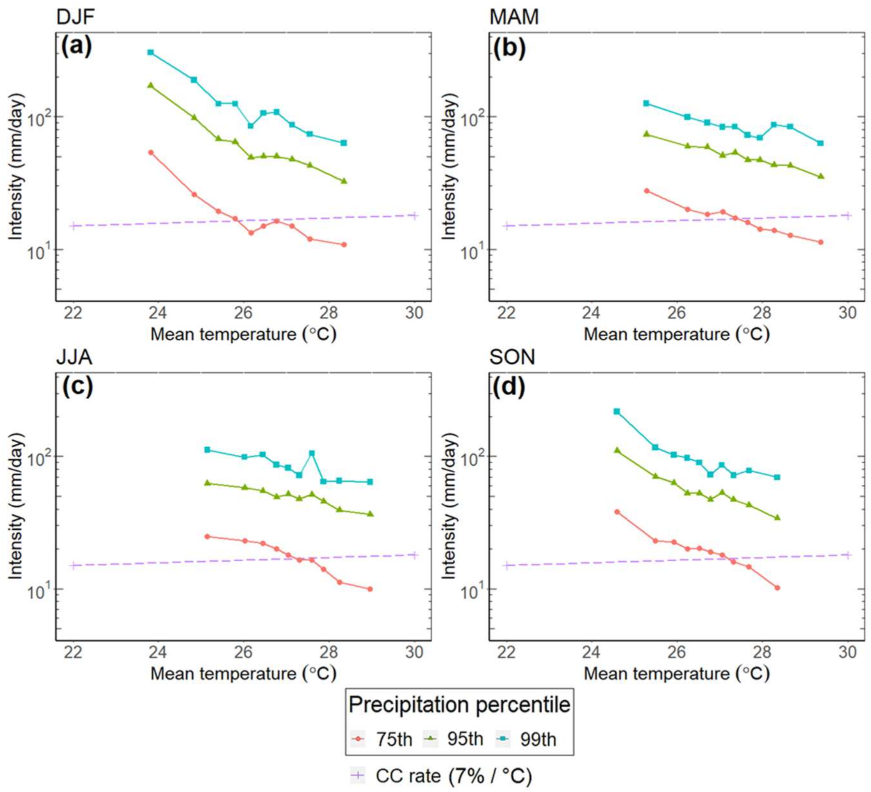

Fig. 5 Similar to Fig. 2, but for seasonal variation in December-February (a), March-May (b), June-August (c) and September-October (d). The dashed purple line indicates CC scaling of 7 % ◦C⁻¹

The trend observed in Fig. 2-5 indicates that rainfall tends to be less intense as daily surface air temperature rises. Further investigations were performed to get a better insight into rainfall behavior as temperature rises. Fig. 6 shows the variation of the ratio of the wet day (defined as a day with recorded rainfall depth of at least 0.1 mm) to total observation day as a function of mean daily surface air temperature for all weather stations investigated.

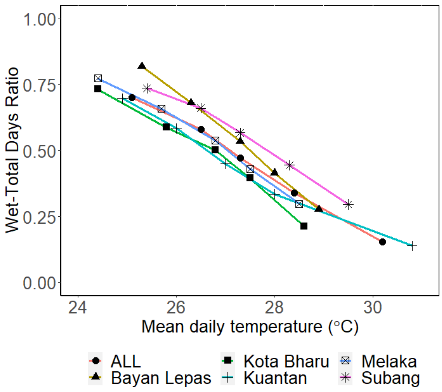

Fig. 6 Variations of wet day to total observation day with mean daily temperature for all weather stations in this study

According to Fig. 6, the wet day-total observation day ratio decreases with increasing mean daily surface air temperature, regardless of individual weather stations investigated. This signals that days that observed higher temperature tends to be drier. The result in Fig. 6 was clearly observed when the monthly variation of mean daily surface air temperature in Fig. 7 from Month 6 (June) to Month 11 (November) was compared with the corresponding monthly variation of the ratio of wet day to total observation in Peninsular Malaysia as shown in Fig. 8.

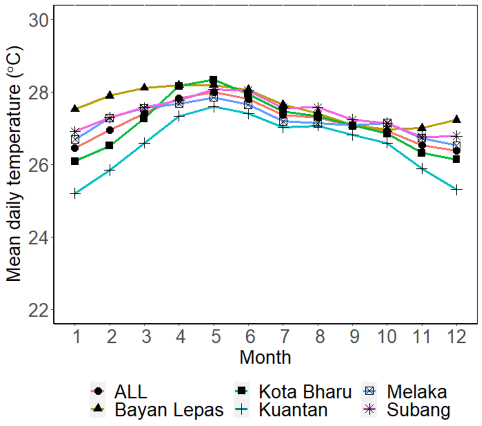

Fig. 7 Monthly variation of mean daily temperature for all weather stations in this study

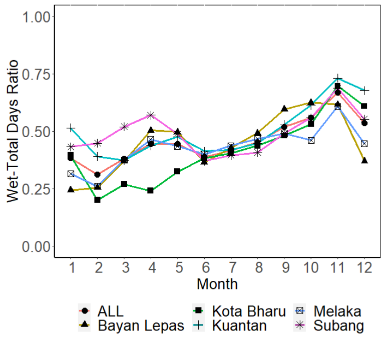

Fig. 8 Monthly variation of the ratio of wet day to total observation day for all weather stations in this study

Fig. 9 further shows the behavior of rainfall with increasing temperature described in Fig. 6-8. Fig. 9 shows the cumulative distribution function of rainfalls at selected temperature intervals obtained by dividing observations into several bins of equal, overlapped temperature intervals. Overlapping bins were used here to avoid biases due to the arbitrary choice of interval and allow wider bins for sample binning when the number of observations is limited [16]. According to Fig. 9, as temperature increases, the intensity of extreme rainfalls is decreasing. Further, at a higher temperature, the probability of rainfall with high rainfall depth decreases. Observation in Fig. 9 thus reflects the observations presented in Fig. 6-8 where the higher temperature tends to occur during drier days, which affects the relationship of extreme rainfall with temperature in Peninsular Malaysia.

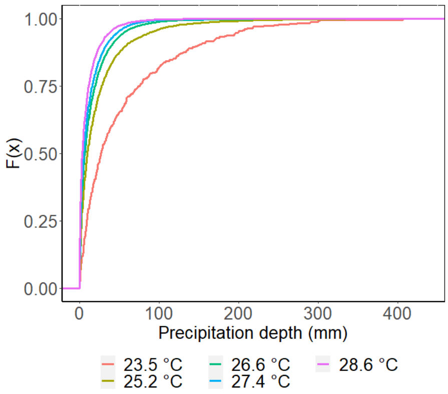

Fig. 9 Cumulative distribution functions, *F*(*x*), for the precipitation depths at different temperature intervals for all weather stations in this study

The overall analysis of the results presented in Fig. 2-9 shows that the observed negative scaling in Peninsular Malaysia may be attributed to the limitation of humidity at a higher temperature [22]. However, the limitation of humidity is not a concern here because Peninsular Malaysia is surrounded by seas that provide a large moisture source in the atmosphere. Citing the study in Israel, which is located beside the Mediterranean Sea, Drobinski *et al.* [10] argued that relative humidity should remain constant due to the increase of moisture availability and uptake as the region warms. However, Drobinski *et al.* [10] showed that the relative humidity in Israel was decreasing at a higher temperature which indicates other factors might be contributed to the observation.

Another possible explanation for the negative scaling observed in the results may be due to the decrease in the duration of extreme rainfall events at higher temperatures rather than the intensity [14], [18]. Although there was a limited study that investigates the relationship of rainfall durations with increasing temperature in Peninsular Malaysia, the fact that there is an increase of temperature in Peninsular Malaysia [3] along with the evidence of higher rainfall intensity at shorter (hourly) rainfall within the period investigated in this study [6] indicates that the influence of rainfall duration to the scaling on extreme rainfalls cannot be dismissed.

Herath, Sarukkalige, and Nguyen [12] highlights that the extreme positive rainfall scaling trend is observed as the sampling time shorter than the daily timescale. Further, Drobinski *et al.* [10] noted the sampling time between 30 minutes and one hour would be sufficient for the analysis, as the averaging effect of binning using observations with sampling time shorter than 30 minutes will no longer affect the rainfall-temperature slope at a higher temperature. Since this study only investigates the relationship of daily rainfalls with temperature, further investigation at sub-daily timescales, at least at hourly timescale as per Drobinski *et al.* [10], are crucial to investigate the possibility of whether a similar negative trend holds at a sub-daily level or follows the CC relationship. This is supported with evidence of higher rainfall intensity at hourly rainfall observed in Peninsular Malaysia within the period investigated in this study by Syafrina, Zalina, and Juneng [6].

IV. CONCLUSION

In this study, the rainfall-temperature relationship at the daily timescale was investigated using data from five weather stations located in Peninsular Malaysia (Bayan Lepas, Kota Bharu, Kuantan, Melaka, and Subang). The scaling was analyzed by considering individual weather stations as well as overall observations from all weather stations at the 50th, 65th, 75th, 85th, 95th, and 99th percentile of rainfall depth against mean daily surface air temperature. Temporal variation of the scaling rate was also considered where the monthly and seasonal scaling rate at 50th, 95th, and 99th percentile of rainfall depth was investigated.

This analysis reveals that the scaling rate of extreme rainfall with surface air temperature departed from the expectation of CC relationship in the negative scaling range regardless of locations and time investigated. The scaling rate tends to be higher for stations located on the west coast of Peninsular Malaysia (Subang and Melaka) and lower in the northern and east coast of Peninsular Malaysia (Bayan Lepas, Kota Bharu, and Kuantan). The scaling rate also tends to be stronger in warmer seasons compared to colder seasons. Further, the scaling rate also varies with percentile, where the 99th percentile always shows a higher scaling rate than the 50th percentile throughout the year, with the high difference in the scaling rate between the 99th and 75th percentile from April to October. It is concluded that the scaling rate of rainfall with temperature is stronger when extreme events are considered or when the surface air temperature is higher.

Finally, the effect of temperature on the amount of rainfall was investigated by considering the ratio of wet day to total observation day as well as the distribution of rainfall at several temperature intervals. The ratio of wet day to total observation day appears to decrease as mean daily surface air temperature increases. Further, the intensity of rainfall also appears to decrease with increasing mean daily surface air temperature. Thus, it is concluded that drier days with less rainfall are apparent in hotter temperatures, which was reflected in the negative scaling trend of the relationship of extreme rainfall with surface air temperature in this study. The results are likely to have an implication on the extreme rainfall projections under future climate.

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