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Trends in Thailand’s Extreme Temperature Indices during 1955-2018 and Their Relationship with Global Mean Temperature Change

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Abstract

Trends in Thailand’s extreme temperature indices and their relationship with global mean temperature (GMT) change are analyzed, based on longer quality controlled temperature data during 1955–2018. Widespread significant trends of extreme temperature indices with a clear warming evident in all indices are observed, consistent with the earlier results and general global warming. Changes associated with the upper tails of the minimum and maximum temperature distributions are the dominant feature of Thailand’s extreme temperature indices accounting for more than 65% of the total variance. Analysis of the probability distribution functions (PDFs) of combined extreme temperature indices further shows significant shifts in their distributions toward warmer conditions in the recent decades. The results suggest that daytime and nighttime temperatures in Thailand have become more extreme and that the changes are related to shifts in multiple aspects of the daily temperature distributions. With long-term temperature records, this study provides more confident and robust evidence of trends in Thailand’s temperature extremes occurred since the second half of 20th century. Another noteworthy finding is that most of Thailand’s extreme temperature indices show a distinct linear relationship with GMT, indicating that local-scale changes in temperatures and its extreme at local scale are related almost linearly to GMT change. The extrapolated values of the indices with strong linearity with GMT show substantial distinction with nearly 50% increase between 2 global warming levels set by Paris Agreement, highlighting that half a degree increase in GMT will lead to greatly increase in Thailand’s temperature extremes.

Keywords: Thailand; Trend; Extreme temperature indices; Global mean temperature

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Introduction

Over the last several decades, changes in temperature extremes have attracted enormous attention worldwide due to their significant impacts on human and natural systems. An increased amount of extensive work reveals widespread significant changes in temperature extremes observed on regional and global scales that are consistent well with warming [1–4]. Model-based studies further show that the frequency and intensity of temperature extremes including prolonged and severe heatwaves are expected to increase as a result of continued human-induced climate change [5–7]. It has been observed that temperature extremes in many regions exhibit a faster change than in the mean temperature [8]. Moreover, an increase in summertime warm extreme occurrences over land has been observed despite during the global warming slowdown taken place after the late 1990s [9]. This emerging evidence calls for further investigation on how temperature extremes have changed in response to background warming especially in local and regional contexts.

Since the Paris Agreement adopted in 2015, the global mean temperature (GMT) has been used as a key proxy to guide global climate actions to hold the global temperature increase to well below 2 ºC above pre-industrial levels and pursuing efforts to limit it to 1.5 ºC [10]. The new agreement brings one of the prominent topics in identifying changes in climate extremes as a function of global warming of different magnitudes. Comprehensive understanding of such changes at local and regional scales which can greatly vary one region to another for a given increment in GMT is of primary importance to avoid the potential risks of anthropogenic climate change and to provide recommendations for country-level policymakers. Recently available evidence has shown that projected changes in temperature extremes are significantly different from each other at the 1.5º and 2º levels of global warming [11–14]. In addition, some studies show that much of absolute changes in climate extreme events can be related almost linearly the past and future changes in GMT [15–16]. Nowadays, several approaches have been developed for analyzing regional climate signals associated with specific global warming levels [17]. One of simple but more robust methods is a linear regression because this approach takes all available data points into account, minimizing the mean-squared error [18].

Based on the quality controlled daily temperature data covering a much longer period, 1955 to 2018, the previous study of Limjirakan and Limsakul (2012) [19] is updated. Long-term local changes in Thailand's temperature extremes in relation to past GMT are also analyzed. If linear relations between them are found, the anticipated changes at 1.5 ºC and 2 ºC will be further extrapolated. This study aims at providing scientific information urgently needed to manage impacts and risks associated with temperature extremes as well as to develop adaptation strategies at the country level in supporting the Paris Agreement implementation.

Data and methods

Daily minimum and maximum temperature data routinely recorded at the main surface weather stations of Thai Meteorological Department (TMD) distributed across Thailand are used. The data are first selected based on record length being available from 1955 to present and completeness with missing data less than 1%. The objective techniques including tests of outliers, data missing interpolation and homogeneity test are employed to evaluate the quality of the selected data [19–21]. Outliers for each series are identified by comparing their values to adjacent days and to the same day at nearby stations before they are edited or removed. The missing values are interpolated by using data from the nearest neighboring stations [22]. Data homogeneity is also assessed based on the penalized t-test and the penalized maximal *F*-test [21], using the R-based RHtests V4 software (see http://etccdi.pacificclimate.org/indices.shtml). This technique is capable of detecting multiple step changes in time series by identifying the changepoints in a two-phase regression model [21]. On the basis of the quality control procedures, a set of 31 high-quality records of daily temperatures for the period 1955 to 2018 is obtained (Figure 1) for further calculation of extreme temperature indices and trend analysis.

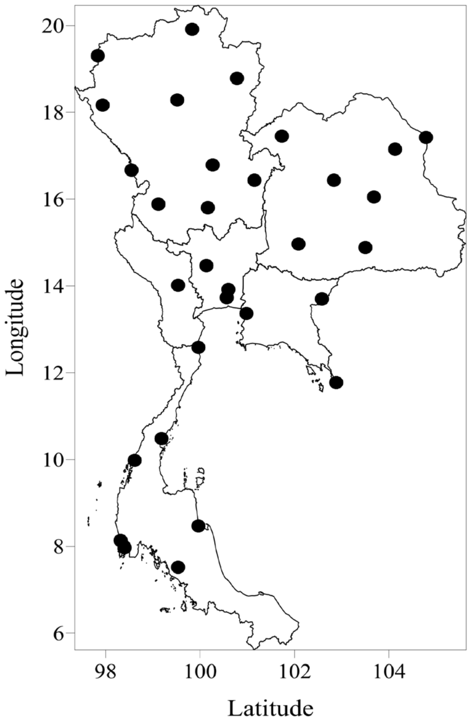

Figure 1 Geographical distribution of TMD's main surface weather stations with long-running quality controlled daily minimum and maximum temperature data during 1955–2018.

In addition, the annual GMT data as global land and ocean combined temperature anomalies relative to the 1951-1980 average obtained from Goddard Institute for Space Studies (GISS) temperature analysis (GISTEMP), National Aeronautics and Space Administration (NASA) (https://climate.nasa.gov/vital-signs/global-temperature) are also utilized. These data are an estimate of global surface temperature change that could be compared with expected global climate change in response to known or suspected climate forcing mechanisms such as atmospheric carbon dioxide, volcanic aerosols, and solar irradiance changes [23]. The GISTEMP combines available sea surface temperature records with meteorological station measurements into a comprehensive global surface temperature dataset spanning 1880 to the present at monthly resolution [23]. As such, it is one of the main datasets used to monitor global and regional temperature variability and trends. The analysis methods including quantitative estimates of the error and homogeneity adjustment is fully documented in Hansen et al. (2010) [23].

The extreme temperature indices including annual means recommended by the World Meteorological Organization (WMO)'s Expert Team on Climate Change Detection and Indices (ETCCDI) (see http://etccdi.pacificclimate.org/indices.shtml) are computed for each of the stations (Table 1). These extreme temperature indices including percentile-based, absolute, threshold and other indices primarily represent changes in intensity, frequency and duration of temperature events. Temperature indices are computed using the R-based RClimDex/FClimdex software package [24]. For comparative purpose with the previous studies, a base period of 1971–2000 is used when computing percentile-based indicators.

A Kendall's tau based slope estimator which has been widely used to evaluate the randomness against trend in hydrology and climatology is applied to assess statistical significance for the trends in extreme temperature indices for each station [1–2, 25–26]. It is non-parametric ranked based procedure which is robust to the influence of extremes, good for use with skewed variables and highly resistant to the effects of outliers [1–2, 27]. A trend is taken to be statistically significant when the probability is at 95% level (p=0.05). Country-wide time series for the years

1955–2018 are also created for every index by averaging the anomalies of all stations to the base period from 1971 to 2000. In addition, the statistical techniques which include Empirical Orthogonal Function (EOF), a 2-tailed Kolmogorov -Smimov (K-S) test and a linear regression model are also used to analyze characteristics of changes in extreme temperature indices in Thailand. The EOF analysis is employed to objectively isolate the most dominant modes of a set of Thailand's extreme temperature indices. The EOF is multivariate statistics which is the most widely used in the climatological data analysis [28–30]. It is principally based on a linear transformation to decompose a m x n data matrix into orthogonal basis functions of physically interpretable patterns of variability, while the variance presented in the original data sets is retained as much as possible [28-30]. The major aim of the EOF is to achieve a decomposition of a discrete or continuous X (t, s) field, where t and s for this study denote respectively time and temperature extreme indices, as Eq. 1.

$$X(t,s) = \sum_{k=1}^{M} c_k(t) u_k(s) \qquad \text{(Eq. 1)}$$

M presents the number of modes contained in the X (t, s) field, using an optimal set of basis functions of (s) and expansion functions of time $c_k(t)$ [28–30]. Before EOF analysis, each of all-station average series of original extreme temperature indices (Table 1) at individual stations is normalized to a standard deviation unit. Whereas, the K-S test is non-parametric statistics commonly used to assess if the PDFs of a particular variable for different time periods are significantly different from each other [31–33]. It is done by comparing two batches of data under the null hypothesis that two PDFs for two time periods are identical.

Table 1 Description and units of the WMO-ETCCDI's temperature indices used in this study

Index	Descriptive name	Definition	Unit
Extremely cold temperature indices			
TN10p	Cold night	Number of days when minimum temperature (TN) < 10th percentile	day
TX10p	Cold day	Number of days when maximum temperature (TX) < 10^{th} percentile	day
TNn	Min. T_{min} (coldest night)	Annual minimum value of daily TN	ºC
TXn	Min. T_{max} (coldest day)	Annual minimum value of daily TX	ºC
DTR	Diurnal temperature range	Mean difference between TX and TN	ºC
CSDI	Cold spell duration indicator	Annual count with at least 6 consecutive days when TN >10th percentile	day
Extremely warm temperature indices			
TN90p	Warm night	Number of days when TN > 90^{th} percentile	day
TX90p	Warm day	Number of days when TX > 90th percentile	day
TNx	Max. T_{min} (warmest night)	Annual maximum value of daily TN	ºC
TXx	Max. T_{max} (warmest day)	Annual maximum value of daily TX	ºC
TR25	Tropical night	Annual count when daily TN > 25 ºC	day
SU35	Summer day	Annual count when daily TX > 35 ºC	day
WSDI	Warm spell duration indicator	Annual count with at least 6 consecutive days when TX > 90^{th} percentile	day

Results and discussions

1) Trends in Thailand's extreme temperature indices during 1955–2018

Analysis based on a longer temperature dataset extended back to 1955 and updated to 2018 reveals widespread significant trends of extreme temperature indices in Thailand (Figure 2 and Table 2). A clear warming is evident in all indices, consistent with the earlier results of Limjirakan and Limsakul (2012) [19] and the overall warming observed at regional and global levels [1–4, 23]. The most prominent feature is the increase in warm extremes and the decrease in cold extremes especially the percentile-based indices which are more robust across country as they often account for the influence of local climate effect (Figure 2 and Table 2). In general, changes are more pronounced in the indices calculated from daily minimum temperature than for those calculated from daily maximum temperature, consistent with the regional results reported earlier [1, 3–4, 23]. This is particularly true for the coldest nights (TNn) and the frequency of warm night (TN90p) which statistically significant increases have occurred at all stations (Table 2).

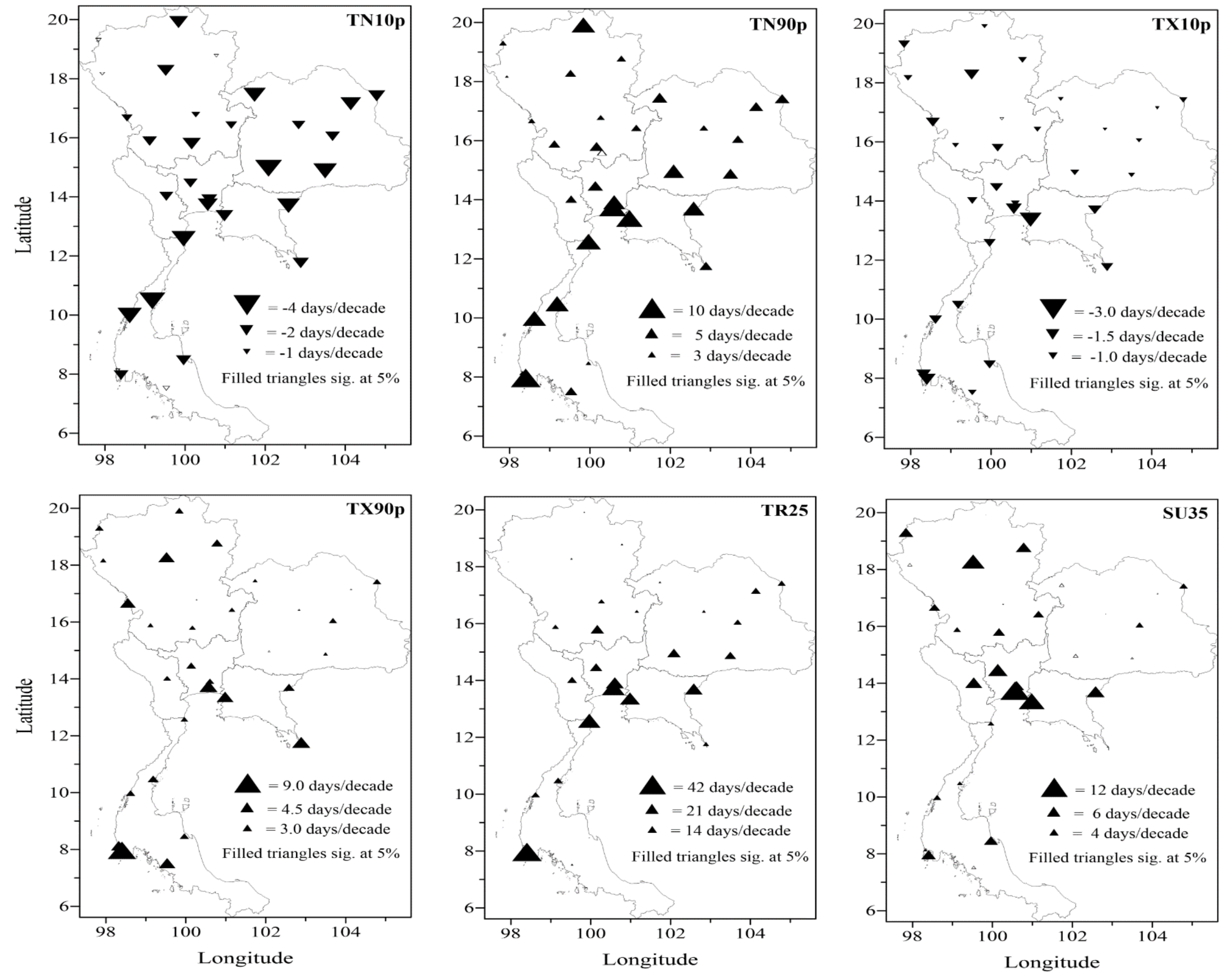

Figure 2 Station-by-station trends per decade for cold nights (TN10p), warm nights (TN90p), cold days (TX10p), cold nights (TX90p), tropical nights (TR25) and summer days (SU35) for period 1955–2018.

For threshold indices, about 90% of the stations show significant changes in the occurrence of tropical nights (TR25) and summer days (SU35) (Table 2). However, there are mixed and weaker trends for the absolute temperature indices (TXn, TXx and TNx) excepting TNn with only 22.6 – 54.8% of stations showing significant trends (Table 2). Choi et al. (2009) [1] and Cesar et al. (2011) [23] pointed out that these indices tend to exhibit more interannual variability than other multiple event-based indices because they are based on a single event in each year which are sensitive to the large variability. As other indices, diurnal temperature range (DTR) shows general decrease with 74% of stations having significant trends (Table 2). The magnitude of changes in extreme temperature indices observed in Thailand are generally comparable with or relatively higher than those in the global and regional averages of the indices [1–2, 4]. Further comparison shows that the patterns and directions of changes in all temperature extreme indices observed in here are similar to those reported in Limjirakan and Limsakul (2012). However, their magnitudes are different from what was detected in the earlier results of Limjirakan and Limsakul (2012) due primarily to different length of data records used. Given longer temperature records employed in this study, therefore, the results provide more confident and robust evidence of trends in Thailand's temperature extremes occurred before the 1970s and recent years after 2009, well representing the changes since the second half of 20th century.

Table 2 Mean and standard deviation of positive and negative trends for each extreme temperature index averaged all stations in Thailand

Index	Negative trend	Positive trend
Percentile indices		
TN10p (days/decade)	-2.1 ± 0.84 (26/31)	
TN90p (days/decade)		5.0 ± 2.4 (31/31)
TX10p (days/decade)	-1.0 ± 0.42 (30/31)	
TX90p (days/decade)		3.0 ± 1.8 (27/31)
Absolute indices		
TNn (°C/decade)		0.58 ± 0.18 (31/31)
TNx (°C/decade)	-0.06 ± 0.05 (0/4)	0.17 ± 1.0 (17/27)
TXn (°C/decade)	-0.13 ± 0.07 (0/15)	0.15 ± 0.07 (7/16)
TXx (°C/decade)	-0.06 ± 0.05 (1/13)	0.14 ± 0.08 (10/18)
Threshold indices		
TR25 (days/decade)		12.4 ± 10.8 (28/31)
SU35 (days/decade)		4.1 ±3.1 (23/31)
Duration indices		
CSDI (days/decade)	-1.3 ± 0.70 (18/26)	0.43 ± 0.19 (0/5)
WSDI (days/decade)		5.2 ± 2.8 (28/31)
Other indices		
DTR (°C/decade)	-0.15 ± 0.090 (23/26)	0.04 ± 0.02 (1/5)

Remark: The numerator and denominator in the parentheses denote the number of stations significant at 95% confidence level and total number of stations, respectively.

2) Dominant mode of Thailand's extreme temperature indices

The EOF analysis reveals that the leading mode of a set of 13 extreme temperature indices in Thailand accounts for greater than 65% of the total fractional variance. The rule given by North et al. (1982) [34] in terms of the sampling error bars indicates that the leading mode is statistically distinguished from the rest of the eigenvectors. The second EOF mode explaining about 13% of the total variance is however not separable from the higher modes. This analysis suggests that the leading mode is a good representative in describing the dominant feature of variability in extreme temperature indices in Thailand as a whole and the higher EOF modes are potentially mixed and seem to be physically non-interpretable. The results based on the loadings as a measure of the relative importance of each of normalized time series in the extracted EOF show that the extreme warm temperature indices (TN90p, TX90p, TNx, TXx, TR25, SU35 and WSDI) are nearly equally important in defining the leading mode. The corresponding coefficient time series associated with the leading mode of extreme temperature indices discloses significant increase during 1955-2018 (Figure 3). A further examination of Figure 3 shows that the rate of change in the leading-mode coefficient time series has more pronounced since the 1980s. Based on these results, it can be said that changes associated with the upper tails of the minimum and maximum temperature distributions are the dominant feature of extreme temperature indices in Thailand with a greater rate of change occurred in the recent years, similar to what has been reported in other parts of the world [1, 4].

3) PDFs of Thailand's extreme temperature indices

Following the approach used by the previous studies [31–32, 35], changes in the respective PDFs for two 32-year periods; 1955–1986 and 1987–2018 are evaluated to illustrate whether the PDFs for these two periods are significantly different or not. Analysis is based on the normalized series of all-station averaged extreme temperature indices. The normalization is widely recognized as the appropriate way to convert different raw data series, taking into account of the mean and standard deviation of each data series, into Z-scores which bring them to a same comparable scale [29]. This method preserves range (minimum and maximum) and introduces the dispersion of series (standard deviation and variance), making the comparison of raw data series with different scales easier and more meaningful [29].

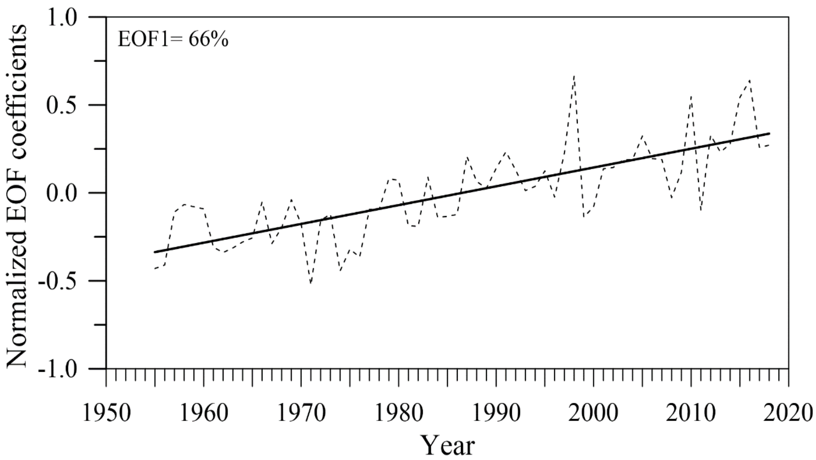

Figure 3 Time-varying coefficient series of the leading mode (EOF1) of 13 extreme temperature indices in Thailand during 1955–2018.

With this approach, the normalized series can be grouped and averaged together as the extremely cold temperature index (TN10p, TX10p, TNn, TXn, DTR and CSDI) and the extremely warm temperature index (TN90p, TX90p, TNx, TXx, TR25, SU35 and WSDI), respectively. Presenting as two cold and warm categories rather than individual index can provide a comprehensive and abstract picture of changes in characteristics of Thailand's extreme temperature indices that is both convenient and easy-to-understand way for policy makers and non-specialist. The PDFs are then calculated using the averaged series of these indices which relative frequencies are counted using a bin width of 0.1. Statistical characteristics of the PDFs such as the higher moments (mean, variance, skewness and kurtosis) are also calculated both for two periods.

The results indicate that the PDFs of both extremely cold temperature index (Figure 4 (a)). and extremely warm temperature index (Figure 4(b)) have significantly shifted toward lower and higher values respectively in the latter period compared to the earlier period. Changes in variance have also become larger in the latter period. Whereas, the asymmetry appears to have decreased between the two periods, becoming positively skewed in more recent decades which indicates a systematic change in shape toward the hotter part of the distribution. A two-tailed Kolmogorov-Smimov test shows that the PDFs between the two periods are statistically significantly different from each other at the 1% level, generally related to a significant shift in the location parameter (mean) of the PDFs. Analysis also suggests that the PDFs of both extremely cold temperature index and extremely warm temperature index in Thailand have shifted toward warmer temperatures with changes in skewness to the hotter part of the distribution and changes in variance becoming wider distribution. These observed changes are somewhat similar to what have been found by Donate and Alexander (2012) [35] who indicate that the PDF of both daily minimum and maximum temperatures in the 1981-2010 period compared to the 1951–1980 period have significantly shifted toward higher values in almost all regions of the world. Based on the results from this study, it can be concluded that daytime and nighttime temperatures in Thailand have indeed become more extreme and that the changes are related to shifts in multiple aspects of the daily temperature distributions other than just changes in the mean, consistent with the results of Donate and Alexander (2012) [35].

4) Changes in Thailand's extreme temperature indices in relation to GMT change

To demonstrate how extreme temperature indices in Thailand have changed as a function of GMT change, a linear regression model with the least-square approach to minimize the residual sum of squares with respect to the regression coefficient is applied. This approach can be viewed as a simple but more robust empirical GMT relationship technique which is a type of hybrid method compared to the four main approaches described in James et al. (2017) [17]. The main advantage of this approach is that it provides information on the response of a given local and regional quantity for different levels of GMT change and an empirical assessment whether such a relationship is linearity or nonlinearity or not. In this analysis, the annual GMT data during 1955–2018 are used as the dependent variable which anomalies of individual all-Thailand averaged extreme temperature indices are regressed on it.

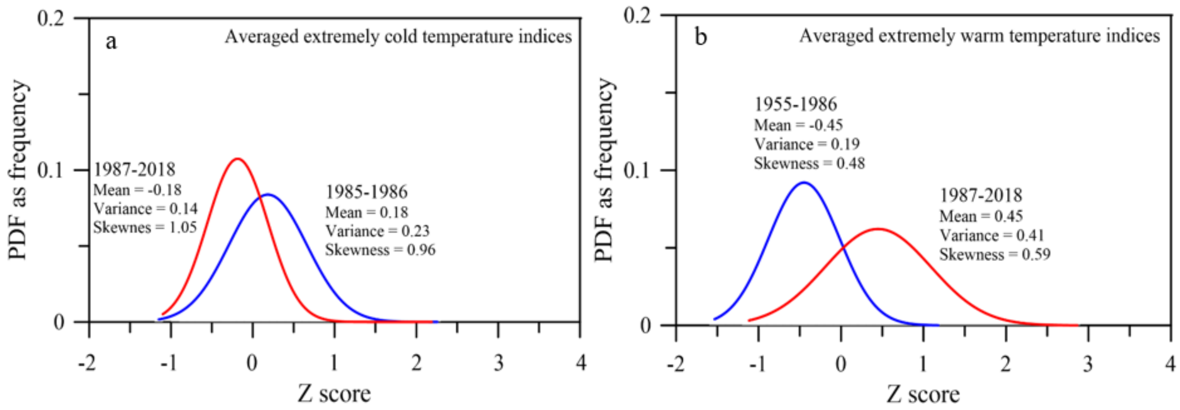

Figure 4 PDFs of (a) averaged extremely cold temperature indices (TN10p (8.0±6.9), TX10p (8.9±4.0), TNn (12.8±4.6), TXn (23.7±2.6), DTR (10.2±1.6) and CSDI (4.6±10.3)) and (b) averaged extremely warm temperature indices (TN90p (16.6±13.1), TX90p (15.0±10.2), TNx (27.4±1.4), TXx (39.1±2.1), TR25 (65.1±63.1), SU35 (62.9±39.8) and WSDI (14.8±21.3)) for all stations across Thailand for two 32-year periods; 1955–1986 and 1987–2018. The values in the parentheses denote mean and standard deviation for each index.

Analysis provides evidence that most of the absolute changes in all-Thailand averaged extreme temperature indices show a distinct linear relationship with GMT. These results indicate that changes in temperatures and its extreme at local scale are related almost linearly to large-scale or global mean temperature changes. The strong linearity can be found for annual means of daily minimum and maximum temperatures, TN10p, TN90p, TR25 and TX90p which GMT variations account for the changes in those indices greater than 70% (Figure 4). Observations from this study are good agreement with the recent studies. Wartenburger et al. (2017) [36] have demonstrated that a number of regionally average climate indices linearly relate to GMT which the linear relationships are particularly obvious for the temperature derived indices and drought and water-cycle indices. In addition, other studies have shown that climate change signals and their associated extremes especially regional and large-scale patterns are often found to be linear as a function of GMT [12–13, 15–16, 37]. However, predictive skills of a linear regression model used in this study is relatively low for some extreme temperature indices especially those based on absolute and threshold definition. Previous studies show that predictive skill of the linear-based model is limited mainly by the degree of linearity of the underlying relationship between GMT and extreme climate indices [37–39]. In addition, it has been observed that the linearity of GMT-extreme climate indices is primarily determined by the shape of the temperature distribution [37]. Due to different shapes of the temperature distributions, Lustenberger et al. (2014) [37] found lower skills of interpolated and extrapolated estimations for cold extreme indices (i.e., TX10p, TN10p) than for warm extreme indices (i.e., TX90p, TN90p). Therefore, the factors mentioned above are believed to be important causes of the observed lower predictive skills based on a linear regression model for some extreme temperature indices in this study.

Anticipated changes at global warming of 1.5 °C and 2 °C for the indices which have strong linearity with GMT (R^2 >0.70) are further extrapolated using the linear regression equations developed above. Table 3 shows that the extrapolated values of those indices in Thailand substantially distinct between 2 global warming levels set by Paris Agreement, and both of them are significantly different from the 2000–2018 means. It is also found that half a degree increase in GMT will lead to increase in the indices shown in Table 3 nearly 50%. These results are in line with the study of Zhu et al. (2020) [14] who evaluated projected changes in temperature extreme indices over Southeast Asia at 1.5 °C and 2 °C global warming levels (GWLs), based on the ensemble of CORDEX simulations. Their results show that the temperature indices increase significantly across the Indochina Peninsula and Maritime Continent at both GWLs, with more pronounced magnitudes at 2 °C GWL. On the basis of analysis from this study, it is reasonably said that GMT can be used as an important predictor of some changes in Thailand's extreme temperature aspects.

Table 3 The 2000-2018 means and the extrapolated values at global warming of 1.5 ºC and 2 ºC for the temperature indices which have strong linearity with GMT (R^2 >0.70)

Index	2000-2018 mean	1.5 ºC	2 ºC
Annual mean of daily max. temp. (ºC)	0.35	1.58	2.23
Annual mean of daily min. temp. (ºC)	0.64	2.15	3.04
TN10p (days)	-4.22	-15.55	-22.01
TN90p (days)	11.90	39.17	55.36
TX90p (days)	7.30	26.28	37.10
TR25 (days)	27.61	96.89	137.13

Remark: The extrapolated values of temperature indices at global warming of 1.5 ºC and 2 ºC are based on the linear regression equation as shown in Figure 5.

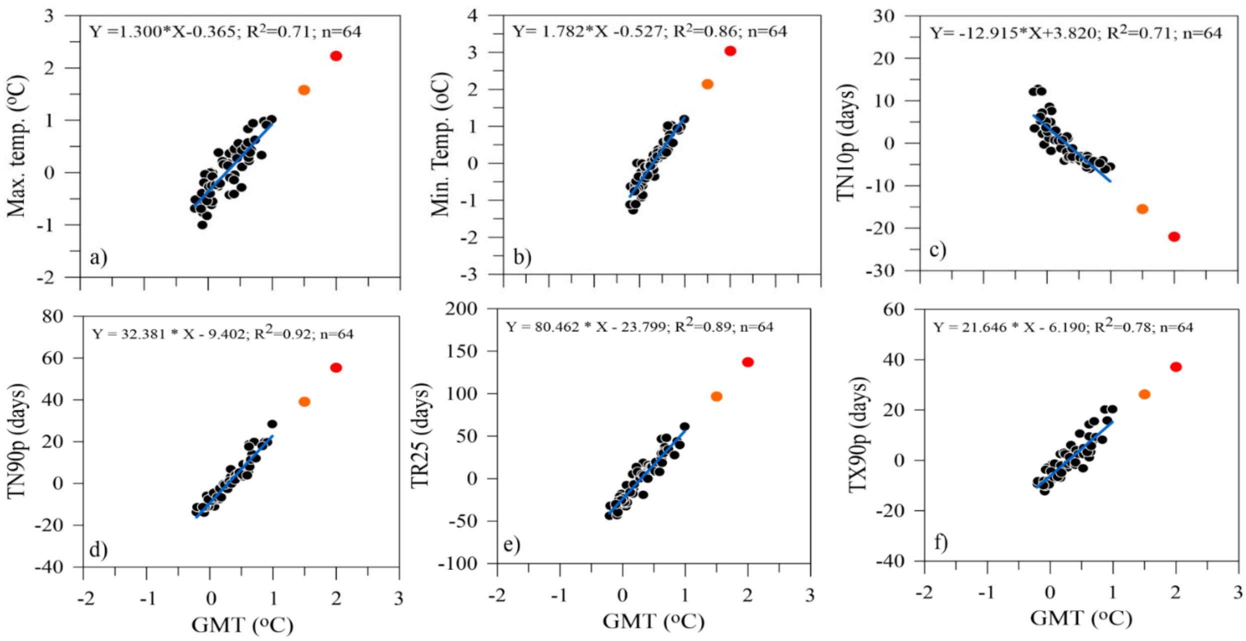

Figure 5 Linear regression-based relationships between global mean temperature (GMT) and some selected Thailand's temperature indices (annual means of minimum and maximum temperatures, TN10p, TN90p, TR25, TX90p). The indices chosen to present in this figure are those with GMT variations accounting for their changes greater than 70%.

Conclusions

Analysis of longer quality controlled temperature data during 1955–2018 disclosures some interesting findings regarding trends in Thailand's extreme temperature indices and their relationship with GMT change which can be summarized as follows;

1) Widespread significant trends of extreme temperature indices in Thailand with a clear warming evident in all indices are observed consistent with the earlier work and the overall regional and global warming. Based on longer temperature records, this study provides more confident and robust evidence of trends in Thailand's temperature extremes occurred since the second half of 20th century.

2) Changes associated with the upper tails of the minimum and maximum temperature distributions are the dominant feature of extreme temperature indices in Thailand accounting for greater than 65% of the total variance with a greater rate of change occurred in the recent years, similar to what has been reported in other parts of the world.

3) The PDFs of the extremely cold/warm temperature index categories derived from daily minimum and maximum temperatures compared between the 1955-1986 period and the 1987-2018 period have significantly shifted toward warmer conditions in the latter period at the 1% confidence level, primarily as a result of combined changes in mean, skewness and variance. These results suggest that daytime and nighttime temperatures in Thailand have become more extreme and that the changes are related to shifts in multiple aspects of the daily temperature distributions.

4) Most of all-Thailand averaged extreme temperature indices shows a distinct linear relationship with GMT, indicating that changes in temperatures and its extreme at local scale are linearly related to large-scale or global mean temperature changes. With these results, it is reasonably said that GMT can be, to greater extent, used as an important predictor of some changes in Thailand's extreme temperature aspects. The extrapolated values of the indices with strong linearity with GMT show substantial distinction with nearly 50% increase between 2 global warming levels set by Paris Agreement, and both of them are significantly different from the 2000-2018 means (>200% and >300% increases at 1.5 ºC and 2 ºC, respectively). These results highlight that half a degree increase in GMT will lead to greatly increase in Thailand's temperature extremes.

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