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Increasing compound hot-rainfall extreme in Thailand during 1970-2022

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Abstract

Compound extremes often result in larger impacts than individual events and have recently received increasing attention. Based on quality-controlled observed data and commonly used empirical-based statistical method, this study examined changes in compound hot-rainfall extreme (CHRE) and their possible contributing factors in Thailand during 1970-2022. Analysis reveals that heavy rainfall preceded by extremely hot weather within three days in Thailand exhibited widespread and significant increases and acceleration in recent years. The results show that increased global mean temperature (GMT) accounted for 66% of Thailand's CHRE changes, while short-term variations in CHRE were significantly correlated (r_s =-0.40) with El Niño-Southern Oscillation (ENSO) events. Moreover, the effects of urbanisation tended to amplify occurrence of CHRE. Our findings highlight that natural-to-anthropogenic climate change and localized urbanisation processes have already expanded the range of climatic hazards in Thailand with their complex combination appearing to dynamically induce back-to-back occurrence of CHRE. Since increased frequency of weather extremes and compound events are expected under a warming world, detection and attribution studies are further required to gain insight of the physical processes and drivers of CHRE, to improve their risk assessment and to develop effective adaptation measures.

Keywords: Compound hot-rainfall extreme, Global mean temperature, Thailand, Trend, Urbanisation

1. Introduction

It has been increasingly recognised that many recent extreme climate events are often caused by the interaction of multiple hazards and drivers. These phenomena are known as compound events that comprise two or more extreme events occurring concurrently, coincidently or successively [1-3]. Compared with individual event, compound events often make the impacts more severe or devastating, leading to larger ecological and socio-economic damages and higher death tolls [2-4]. Evidence shows that many major catastrophes caused by weather and climate extreme events are inherently of a compound nature [2,5,6]. For example, the compound dry-hot extreme occurred in Russia in the summer of 2010 triggered wildfires and air pollution with more than one million hectares burned, resulting in more than 50,000 deaths, a 25% reduction in annual crop production, and total economic losses of approximately 15 billion United States Dollar (USD) [6,7].

As compound events amplify impacts and heighten risks to natural and human systems and are expected to increase in a warming world, several compound events have been increasingly investigated in many regions of the world [4,6,8,9]. On the basis of observations and reanalysis data from the period 1980–2014, Ridder et al. [4] analysed 27 hazard pairs and identified remarkable changes of compound events in many regions of the world. The increased severity of concurrent dry and hot extremes over global land areas including western United States (US), western Europe, Africa, southeastern Asia, and eastern Australia was reported by Hao et al. [8].

Compound hot-rainfall extreme (CHRE) is one of the most important compound extremes, affecting population, ecosystem and a variety of socioeconomic aspects more adversely [5,10]. Despite its importance, few studies have been conducted compared to compound drought and hot extremes [2,3,8]. Therefore, investigation of changes in CHRE, especially in the tropics where hot weather and heavy rainfall are critical extreme events in hydroclimatology [5], is undoubtedly essential for developing effective measures to manage this high-impact phenomenon. In Thailand, 86 severe flood events were reported during 1970-2021, causing more than 61 million people affected and total economic losses of about 47.5 billion USD [11]. Recent estimation also shows that about 46 million of Thai population have been exposing extreme heat [12]. Thus, the efforts to reduce the risks and respond to the adverse impacts of climate-related disasters and their compound events are top national agenda as recently addressed in Thailand's National Adaptation Plan [13]. To the best of our knowledge, all climate change studies conducted in Thailand so far have focused solely on analysis of a single variable especially temperature and rainfall extremes, and examination of their changes in relation to large-scale natural and anthropogenic-induced climate phenomena as well as localized urbanization [14-16]. Building on earlier works to advance the current understanding of these important issues, the present study analysed trends and variability of bivariate compound events related to CHRE in Thailand based on observed station data during the period 1970-2022. The reason behind our motivation is that the occurrence of heavy rainfall after extremely hot weather is a common combined climate event which can be observed across Thailand. The sequence of these climate events often causes heat stress followed by flash flood especially in the urban area. The relationships with global mean temperature (GMT) and El Niño-Southern Oscillation (ENSO), and possible urbanisation effects were further examined.

2. Materials and methods

2.1 Data used

Daily data of air maximum temperature (T_{max}) and rainfall observed at near-surface weather stations located across Thailand were used. These data were obtained from the archives of the Thai Meteorological Department (TMD). Complete daily data for calculating extreme climate and compound indices were chosen on the basic of a number of days with missing data [17]. A month has complete data if there are fewer than 6 days of missing data, while a year with complete data if all months have missing data less than 6 missing days. A total of 68 stations with data covering the period 1970-2022 passed these criteria and were initially selected for quality and homogeneity tests.

Annual anomalies of global surface temperature relative to the 1951-1980 average from Goddard Institute for Space Studies (GISS) surface temperature analysis (GISTEMP) were also employed [18]. The gridded GISTEMP, spanning from 1880 to the present with a monthly resolution, is one of global temperature datasets widely applied to monitor global and regional temperature variability and trends [19,20]. The GISTEMP analysis was based primarily on land surface temperature data derived from the most recent homogenized Global Historical Climatology Network (GHCN)'s station records and the most recent gridded $2^{o}x2^{o}$ sea surface temperature data from Extended Reconstructed Sea Surface Temperature (ERSST) [19,20]. The operational GISTEMP development contained two major steps: interpolation of individual station data and averaging of interpolated fields. Prior to these two core steps, the station data from GHCN had been subjected to extensive quality control including homogeneity check to minimize local errors as well as to guard against_inadvertent errors in data processing and verification of any added near-real time data [19,20]. The GISTEMP performed all calculations on an equal-area grid of 8,000 grid cells with final estimates converted to a regular $2^{o}x2^{o}$ grid. The Southern Oscillation Index (SOI) retrieved from National Center for Atmospheric Research was also used to represent the evolution and development of El Niño or La Niña events in the Pacific Ocean [21]. The SOI fully reflects the behavior of the Walker Circulation and is better to correlate with remote climate variables than other ENSO indices, because of its calculation based on the pressure differences between the centers of ENSO action (Tahiti and Darwin) [21].

2.2 Quality and homogeneity tests

To ensure the integrity and confidence of our analysis, the objective statistic approaches were further used to examine the quality and inhomogeneity of the selected daily T_{max} and rainfall data [22,23]. Internal consistency such as the same T_{max} values for several consecutive days and T_{max} and rainfall outliers were first checked, followed by missing data interpolation. Outliers in the daily series were tested by comparing them with adjacent and same-day values of neighbor stations [22]. Potential outliers of daily T_{max} and rainfall data were first flagged if they were unusually lower or higher than the adjacent and same-day values of neighbor stations [22]. Available metadata and the expert knowledge of local climate conditions were then checked to validate, edit and remove these identified potential outliers. A regression approach with the values at nearby stations was applied to interpolate missing data [22]. The values at selected nearby stations were the independent variable. The penalised maximal *t* (PMT) test was applied to evaluate inhomogeneities of the data series caused by any existing undocumented non-climatic influences such as station relocation, changes in observing procedures, instruments, and surrounding environments [23,24]. To assess inhomogeneities of the data series resulted from any non-climatic influences such as station relocation, changes in observing procedures, instruments, and surrounding environments, the penalised maximal *t* (PMT) test was employed [23,24]. Multiple step changes presented in the data series were identified by a two-phase recursive regression model, using the freely R-based RHtest software [24,25]. Three stations with significant step shifts in T_{max} and rainfall series were identified. A clear explanation of the possible causes of these identified step shifts cannot be drawn from available station history metadata. The identified inhomogeneous series were then removed for further analysis, because of complexity with substantial uncertainties of the adjustment of inhomogeneous daily data. Finally, 65 stations of daily T_{max} and rainfall were finally obtained for subsequent analysis. Spatial distribution of quality-controlled daily T_{max} and rainfall data during 1970-2022 used in this study was shown in Figure 1. Each weather station is marked as urban or non-urban station based on the classification conducted by Kachenchart et al. [26] and Pimonsree et al. [16].

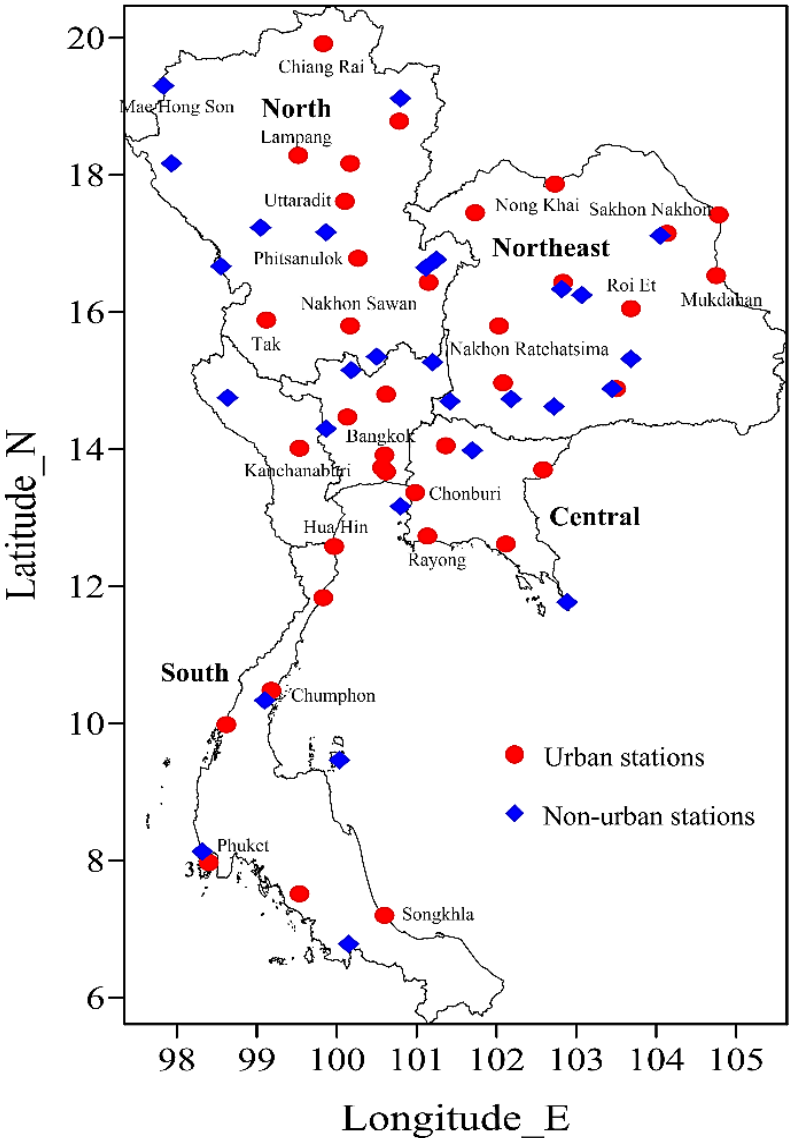

Figure 1 Spatial distribution of daily rainfall and maximum temperature data during 1970-2022 used in this study.

2.3 Compound extreme indices

The empirical method was applied since it is a statistical approach commonly used to analyse multiple variables of compound extremes [2,3,6]. It was executed by counting the number of two or more different extremes occurring coincidentally or sequentially within a certain window of time. The individual extreme was first defined, followed by calculating the quantity of compound extremes on the basis of the concurrent or successive occurrence of individual extremes [2,6]. In this study, the CHRE was calculated from daily T_{max} and daily rainfall for each station individually. Percentile-based hot and rainfall extreme indices were first computed as when daily T_{max} or daily rainfall was larger than 90th percentile values for the reference period of 1970-2005 [2,5,10]. The calculation of these indices was strictly followed the method developed by the Expert Team on Climate Change Detection and Indices (ETCCDI) of the World Meteorological Organization and World Climate Research Program as its methodological details provided in the ETCCDI website [27]. A 36-year climatological normal was chosen as it provided the calculation of percentile-based temperature and rainfall extreme indices in Thailand more robust than the shorter based periods. Previous studies both global and national scales have defined CHRE as the occurrence of extreme rainfall event followed or preconditioned by a hot extreme within three days [5,10,28]. This simple method is robust measure to quantify synchronization and time-delay patterns of hot and rainfall extremes with the key advantage of automatically distinguishing between a pair of event series at different times or locations [29]. On the basis of plausible physical process, the 3-day window has been_selected as an appropriate dynamic time-lag interval that extremely hot weather and sensible heat flux can provide favorable conditions for the development and maintenance of heavy rainfall [29]. This time interval is relevant to Thailand's climate pattern. In the present study, the CHRE was then counted if hot events occur within three days before the starting day of the extreme rainfall event [2,5,10]. We also examined the different thresholds (e.g., 95th and 97th percentiles) to test the robustness of our analysis. It was found that CHREs at the 95th and 97th percentiles were much lower than that defined at the 90th percentile, and estimated trends in CHRE changed across different defining thresholds. Therefore, following the previous studies [5,10], the 90th percentile criterion was selected for analysis in this study because it can extract more CHRE in Thailand than the 95th and 97th percentiles. Adoption of the 90th percentile also made trend analysis more statistically robust.

2.4 Statistical analysis

Linear trends and their statistical significance of annual frequency series of CHRE for each station and for Thailand as a whole were assessed by a non-parametric Mann-Kendall (MK) test [29]. This method is based on ranked measurements which are more statistically robust to the effect of outliers and variables with non-normal distribution [30]. To account for autocorrelations in the time series, a modified method proposed by Hamed and Rao [31] was used. Maps for station-by-station trends were made to illustrate spatial patterns. The anomalies relative to the 1970-2005 base period for all stations were used to computed a country-wide time series. To examine the degree of relationships between Thailand's CHRE and GMT and SOI, Spearman's rank order correlation was also applied.

3. Results and Discussion

3.1 Spatial distribution and trends of CHRE in Thailand

During 1970-2022, CHRE was detected in all parts of Thailand, and observed at each station in the range of 1 to 10 events per year. 36.7% and 26.1% of CHRE occurrences were found at the stations located in the Central and North, respectively. Most of the CHRE (87%) occurred during the hot to early rainy season (March-June). Figure 2 shows station-by-station trends in annual frequency of CHRE with the upward/downward-pointing triangles denoting increasing/decreasing trends and significant changes at the 5% level indicated by filled red and blue triangles. In the long-term context, trends of CHRE were spatially dominated by widespread increases (97%) across Thailand (Figure 2). A total of 39 stations (60%) recorded significant increasing trends in CHRE at the 0.05 confidence level, with their magnitudes in range of 0.23 to 0.99 events per decade (Figure 2). The stations located in the Central and South were marked by larger increases in the CHRE trends (Figure 2). Moreover, the exceptionally large significant trend magnitudes of the CHRE (0.41-0.99 events per decade) can be observed in the Bangkok Mega-city. These results agree well with the study of Pimonsree et al. [16] showing that the Bangkok Mega-city faced significant increases in rainfall extremes together with a concomitant rise in extremely high temperature as a result of the combined effects of urbanisation and anthropogenic-induced climate change. Figure 3 illustrates trends in CHRE for the whole Thailand presented as the all-station average anomalies with the 95% confidence intervals denoting by think grey lines exhibited a significant increase at the rate of 0.22, 0.33 and 0.56 events per decade for the 1970-2022, 1990-2022, and 2000-2022 periods, respectively. The stronger rates of changes in the later periods highlight that CHRE in Thailand tended to occur more frequently in recent decades. Our analysis is consistent with the recent work [10], illustrating that the CHRE frequency in South China during 1971-2017 increased by 0.25 events per decade.

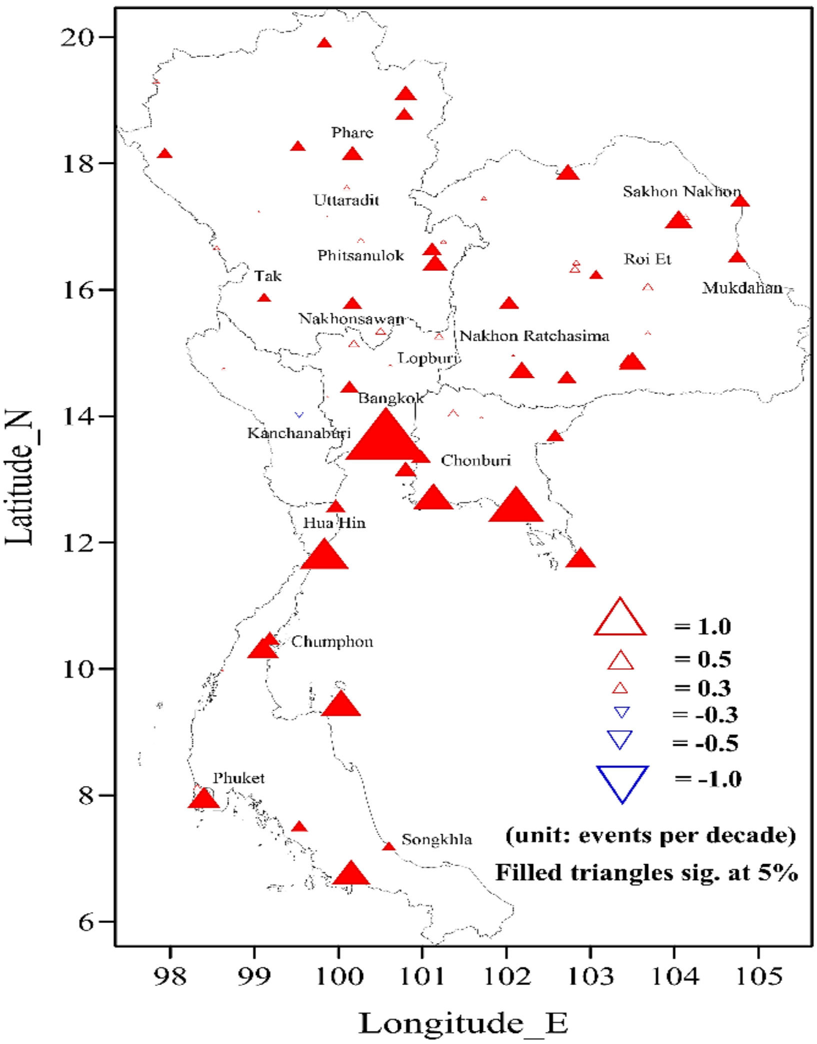

Figure 2 Spatial distribution of trends in annual CHRE frequency during 1970-2022. The upward red (downward blue) triangles represent increasing (decreasing) trends, while statistical significance at the 95% confidence level is denoted by filled red and blue triangles.

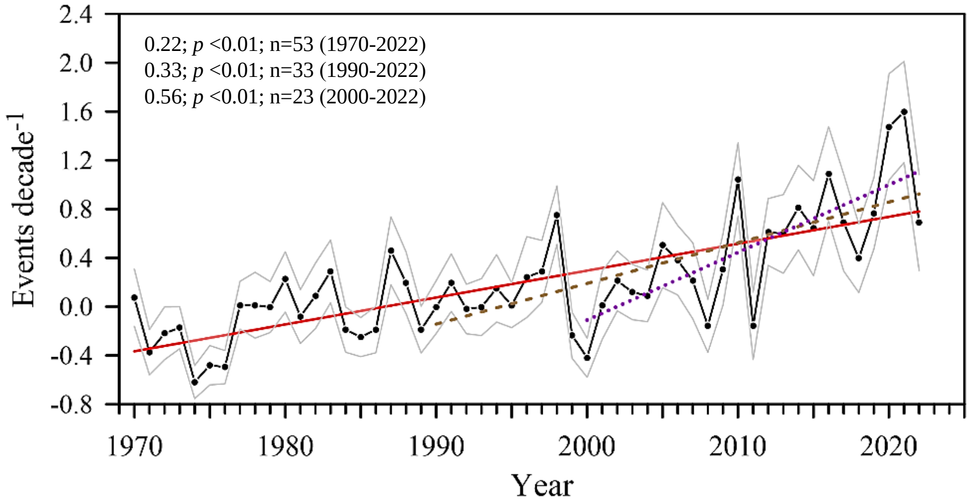

Figure 3 Trends in all-station average anomalies for annual CHRE frequency in three different periods (1970-2022, 1990-2022, and 2000-2022). Thin grey lines are the 95% confidence intervals.

3.2 Relationships of Thailand's CHRE with GMT and ENSO

Analysis disclosed highly significant correlations between GMT and Thailand's CHRE (r_s = 0.82; p<0.01; n=53). Similar significant correlations between GMT and most of extreme temperature indices and contribution trends of light and heavy rainfall events in Thailand were also documented in the studies of Limsakul [32,33]. These results highlight that the occurrence of temperature and rainfall extremes and their compound events in Thailand tended to increase under ongoing human-induced climate change over the past 53 years (1970-2022). Surface air temperature in Thailand was reported to significantly increase by nearly 1ºC over the 50-year period (1970-2019) [26]. Rising atmospheric moisture according to the Clausius-Clapeyron relation is expected to be a consequence of this increase and therefore lead to enhanced occurrence of extreme rainfall events in Thailand as observed by Limsakul and Singhruck [15] and Limsakul [33]. Furthermore, the increase in extremely hot weather in Thailand [16,34,35] can induce heatwave and extreme rainfall events more tightly associated in time and consequently may result in a substantial increase in their compound events as observed in this study. Our results are consistent with recent studies illustrating that CHRE is becoming more frequent under warmer climate conditions, owing primarily to nonlinear increase in hot extremes induced by anthropogenic climate change, particularly in the tropics [5,10,36]. Enhanced convective available potential energy due to higher surface temperatures and increased sensible heat flux after the onset of extremely hot weather as suggested by prior studies [5,36,37] is believed to be one of contributing factors of increased trends in the extreme hot and rainfall sequence in Thailand.

A least-square linear regression between GMT and the average anomalies of CHRE as its plot shown in Figure 4 was further analysed to quantify Thailand's CHRE variations in relation to GMT change. This approach minimises the residual sum of squares with respect to its coefficient. When regressing the GMT as the independent variable on Thailand's CHRE, coefficient of determination (R^2) was 0.66 with the statistical significance at the 0.01 confidence level (Figure 4). These results indicate that variations in Thailand's CHRE are related quite linearly to GMT change which accounted for 66% of total variance. Based on the regression analysis, it is implied that the CHRE in Thailand increased by 0.71 events per decade as the GMT rose by 1°C.

In addition, correlations of residuals of Thailand's CHRE, after removing linear trends, with SOI were significant (r_s = -0.40; p=0.01; n=53 (Figure 5). The relationships suggest that year-to-year variations in Thailand's CHRE tended to be higher-than-usual (lower-than-usual) during the El Niño (La Niña) years. Our analysis provides additional evidence extending our knowledge that ENSO events are a crucial remote forcing influencing interannual variability of rainfall extreme and extremely hot weather including their compound events in Thailand [15,34]. Lin et al. [38] show that El Niño events exert their effect on hot extremes and heatwaves in Indochina through an anomalously sinking motion over the western North Pacific (WNP) and Asia as a result of a weakened Walker circulation, accompanied by the intensification and westward extension of the WNP anticyclone. A new regional insight on how ENSO influences Indochina Peninsula monsoon rainfall has been illustrated by a recent review, highlighting that westward propagation of anomalous circulations in the WNP and South China Sea, together with alternations of the convergence of atmospheric moisture and convection cells associated with shifts in equatorial Walker and regional Hadley circulations are a major mechanism [39]. With this scientific information, a possible cause of the CHRE-ENSO relationship observed in this study seems to be linked to changes in moisture convergence and shifts in convective cells and associated latent heat flux in the WNP forced primarily by sea surface temperature anomalies in the eastern Pacific [15].

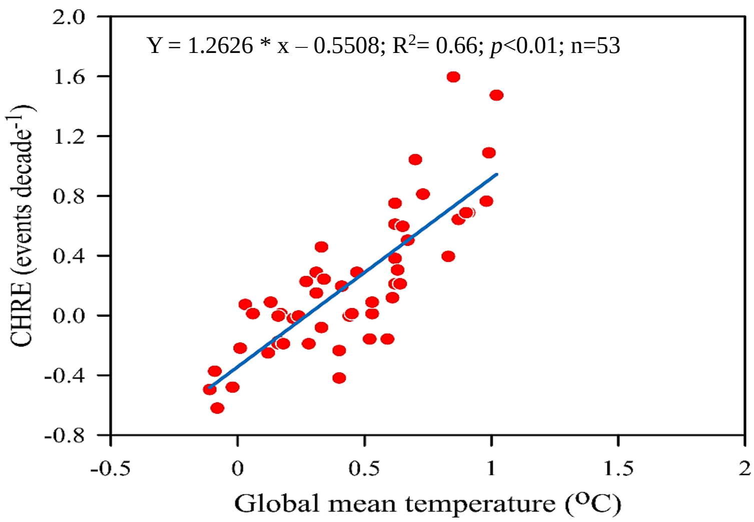

Figure 4 A least-square linear regression between GMT and average CHRE anomalies for Thailand as a whole.

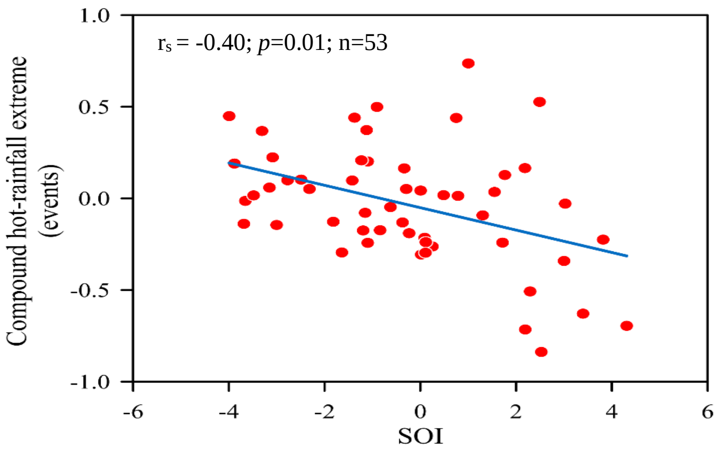

Figure 5 Correlations between SOI and the residuals of the whole Thailand CHRE. Note that negative (positive) values of the SOI represent the El Niño (La Niña) years.

3.3 Effects of urbanization on Thailand's CHRE

To examine the possible effects of urbanisation on the increases in the frequency of the CHRE, classification of all weather stations into urban and non-urban (suburban and rural) types conducted by Kachenchart et al. [26] and Pimonsree et al. [16] was applied. They had first defined urban-type and non-urban-type stations based on the proportion of urban and built-up areas to green areas within a 2.5-km radius centred at each station derived from recently available high-resolution imageries. Classification of urban and non-urban stations based on land-use types had been subsequently rechecked with the updated and complete version of population data at the sub-district level where each weather station is located [16,26]. More details of classification of urban and non-urban stations can be found in Kachenchart et al. [26] and Pimonsree et al. [16]. With these data, 37 urban stations and 28 non-urban stations had been classified (Figure 1). Our analysis reveals that the national average anomaly time series for both types of stations exhibited significant increases in the CHRE frequency. However, larger trends were observed in the urban station time series than the non-urban station time series, indicating a noticeable contribution of urbanisation (Figures 6). Trends in the CHRE for the urban-non-urban differences were 0.07 events per decade with statistical significance at the 0.01 confidence level (Figures 6). Therefore, effects of urbanisation accounted for 28% of the total increasing trends in the frequency of the CHRE in the urban area. These results highlight that the effects of localised urbanisation-driven processes, especially through altering moisture fluxes, thermal characteristics and atmospheric instability in the lower boundary layer including urban aerosols and pollutants as discussed in earlier studies [10,16,40], tend to amplify occurrence of the CHRE in Thailand, in addition to large-scale climate variability and change. Our study is in line with the study of Wu et al. [10], illustrating local urbanization contributing to 40.91% of significant increases in the CHRE frequency in South China. As urbanisation in Thailand has been steadily continued, a deeper investigation through climate model-based dynamical simulations together with detection and attribution studies based on high-resolution satellite data is further needed. This future work will provide the detailed and complex mechanisms underlying the effects of other urbanisation processes such as urban expansion and urban heat island intensity on CHRE.

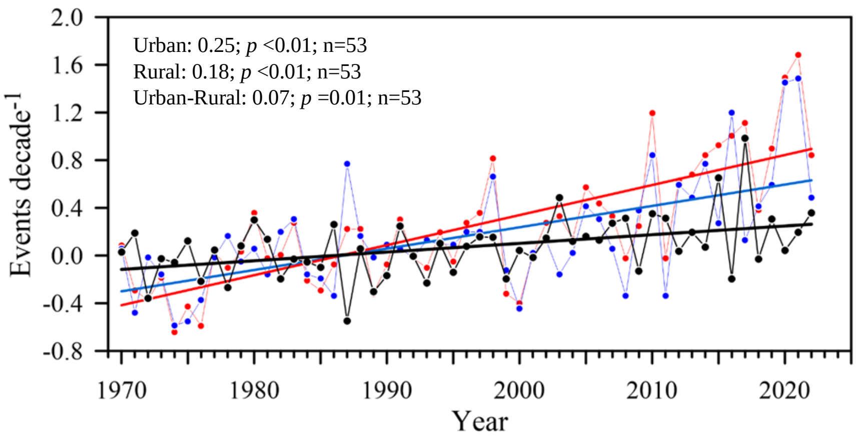

Figure 6 Trends in average anomalies of annual CHRE frequency for urban stations (red), non-urban stations (blue) and urban-non-urban differences (black).

4. Conclusions

This study presents new evidence that CHRE in Thailand has risen. It also highlights that natural and anthropogenic climate change and urbanisation have already expanded the range of climatic hazards with their complex combination appearing to dynamically induce back-to-back occurrence of CHRE at a local scale in the tropical country. Since climate extremes are likely to increase in a warming world, this type of compound extreme events is expected to become more frequent in Thailand. Therefore, detection and attribution studies are further needed to gain insight of the physical processes, drivers and projected changes of CHRE based on recent downscaled climate data simulated under different scenarios of future greenhouse gas emissions. This work will provide more insights of underlying physical mechanisms and interactions among large-scale climate phenomena that shape the occurrence of CHRE in Thailand. It also forms the foundation of comprehensive assessment of risks and development of effective adaptation measures to compound events so as to build resilience to climate change impacts in Thailand.

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6. Author Contributions

Paengkaew, W.: Supervision, Conceptualization, Methodology, Writing – original draft, Writing – review & editing; Limsakul, A.: Funding acquisition, Conceptualization, Methodology, Writing – original draft; Aroonchan, N.: Formal analysis, Visualization, Writing – review & editing; Santisirisomboon, J.: Resources, Formal analysis, Writing – review & editing; Amnuaylojaroen, T.: Software, Formal analysis, Writing – review & editing; Srisawadwong, R.: Software, Formal analysis, Writing – review & editing; Wang, L.: Validation, Conceptualization, Writing – review & editing.

7. Conflict of interest

The authors declare that they have no conflict of interest.

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