

Trends of hot extremes in Thailand during 1970-2024 and increased population exposure

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ABSTRACT

Trends in three nonoverlapping types of hot extremes (independent hot day [IHD], independent hot night [IHN], and compound hot event [CHE]) during the hottest month in Thailand were analyzed for the period 1970-2024. Analysis shows that Thailand experienced more frequent, longer duration, and stronger intensity of IHN and CHE. Their frequency, intensity and duration tended to accelerate in recent years, consistent with a step-up in the warming rate of global surface temperature. Another feature associated with the nighttime-accentuated events is that hot-extreme types in Thailand as a whole shifted from a gradual decline in IHD to the dominance of increasing IHN and CHE. Estimation of population exposure to hot extremes demonstrates that from 2002 to 2024, total population exposure to IHN and CHE at the selected 62 districts where the weather stations are located increased by more than 145% relative to the 2002-2006 period. The change in exposure to hot extremes was mainly caused by climatic effects (99.8%-182%), highlighting that increased hot extremes by themselves substantially escalate population exposure in the selected districts. Continuous exposure to sustained period of hot extremes may bear larger health risk in the coming years, as Thailand's transition to an ageing society is accelerating. However, additional studies based on available high-resolution gridded population and climate projections in combination with epidemiological, demographic and socioeconomic data are needed. Their results will provide a full picture of changes in different types of hot extremes and how the whole Thai population will be exposed to them in the future

Keywords:

hot extremes, compound hot event, exposure, Thailand

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INTRODUCTION

It is increasingly recognized that hot extremes are directly influenced by anthropogenic climate change, significantly affecting human health, the economy, and ecosystems. Hot extremes persistently occurring during summer are often associated with high incidence of morbidity and mortality rates.¹ They also have adverse impacts on crop production, workplace productivity, ecosystem services and biodiversity, wildfires, air and water quality, and public infrastructure.²⁻⁵ A number of studies have consistently shown that the frequency and intensity of hot extremes have increased worldwide over recent decades.⁶⁻⁹ Under a future human-driven global warming, hot extremes will be more frequent and severe at global and continental scales and in nearly all inhabited regions.^{6,7} The frequency of the present-day climate 100-year hottest daily temperature is projected to increase by 200% and more than 700% at the 1.5°C and 2°C warming levels, respectively.¹⁰

Traditional studies focus primarily on either daytime or nighttime hot extremes. This univariate definition potentially fails to identify compound hot extremes that accumulate and aggravate impacts of daytime and nighttime heat.^{1, 7, 11} The single-variable-based approach also hinders our ability to realize notable distinctions in physical mechanisms and long-term trends among daytime, nighttime, and compound hot extremes.⁷ Substantial differences in terms of meteorological mechanisms, impacts, and temporal variations between compound hot extremes and independent hot days or nights have been documented by some studies.^{1, 6-8} Therefore, the more destructive impacts of these events on natural systems and human health may be overlooked by most previous studies.

A number of works have been conducted recently to investigate day-night sustained hot extremes based on a new classification scheme and to distinguish the impacts from different types of hot extremes.^{1, 5-8,12} New evidence shows significant increases in Northern Hemisphere average frequency and intensity of summertime compound hot extremes during 1960-2012, which are projected to continue to rise by about eightfold and threefold, respectively, by 2100.⁶ Based on this study, end-of-century population exposure to compound hot extremes is projected to be four to eight times relative to the 2010 level. Significant increases in frequency, duration, and intensity of compound hot extremes were also detected over most global urban areas.⁸

Knowledge about hot extremes and their population exposure remains too scarce in Thailand which is recognized as one of the most vulnerable countries to climate change. In fact, previous studies carried out in Thailand have focused solely on the analysis of either hot days or hot nights separately, and examination of their changes in the context of large-scale natural and human-caused climate variability and change as well as local-scale urbanization.¹³⁻¹⁵ To the best of our knowledge, combined day-night hot extremes and their impacts have not been investigated yet. To advance the current understanding of these important issues and to gain insight into the knowledge gaps above based on the earlier work, the primary objectives of this study are to first analyze trends in three types of hottest-period hot extreme events (independent hot day [IHD], independent hot night [IHN], and compound hot extreme [CHE]) in Thailand during the period 1970-2024, and to subsequently estimate district-level population exposure to each type of hot extremes. The relative importance of climate, population, and their compounding

effects in driving the exposure change is also discussed. This scientific knowledge is particularly important to effectively design additional responses to different types of hot extremes under ongoing anthropogenic-caused climate change and a significant shift in Thailand's demographic structure due to a rapidly aging society.¹⁶

METHODS

Data used

A long-term daily dataset of minimum ($T_{\min}$) and maximum ($T_{\max}$) temperature for the 1970-2024 period measured at the near-surface weather stations located across Thailand for the hottest period (March to May) was used in this study. These station data were extracted from the archive of the Thailand Meteorological Department (TMD). Major stations of the TMD's near-surface weather stations started before the 1970s with more stations having been steadily installed to improve spatial coverage thereafter. Preliminary checks for data quality are regularly conducted both in real-time and postprocessing. Station data were selected based on the criteria of a number of days with complete and missing data.^{8,11,12} A hottest period is considered to have complete data if there were four or fewer missing days, while a station was considered to have a complete series if all hottest periods for the entire record had fewer than five days of missing data.^{8, 11,12} To assure scientific robustness and reliability of our analysis, the selected data were further examined for quality and homogeneity based on the objective statistics approach.^{17,18} Missing data were interpolated by a spatial regression method using nearby stations. Any existing undocumented inhomogeneity in the data series was additionally evaluated by the penalized maximal t (PMT) using the RHtestsV3 software package. Multiple step changes presented in the data series were identified by a two-phase recursive

regression model.¹⁹ On the basis of the strict quality control and homogeneity tests, 65 stations of daily $T_{\min}$ and $T_{\max}$ were finally obtained for subsequent analysis (Figure 1). In the earlier studies, these quality-controlled station data had been classified as urban type (37 stations) and non-urban (suburban and rural) type (28 stations) as shown in Figure 1, based on land-use types surrounding each weather station derived from high-resolution imageries and sub-district population.^{15,20} Detailed methodology of classification of urban and non-urban stations can be found in Pimonsree et al.¹⁵ and Kachenchart et al.²⁰

High-resolution gridded population data are commonly used to estimate population exposure to climate events.^{21,22} However, reliable and fine-resolution spatial data of past-to-future population are scarce for Thailand. To match point weather station data with irregular space and uneven distribution, we employed total population data at the districts where the meteorological stations are located to estimate exposure to different types of hot extremes. Annual total district population records available for the 2002-2024 period were extracted from the official statistics registration system of the Department of Provincial Administration.²³ There are two districts where two weather stations are situated in the same district boundary. Moreover, data are not available for Ko Si Chang district. Finally, we obtained 62 districts for population exposure analysis. These data are officially registered Thai population recorded based on national ID, providing a vital demographic measure for Thailand and offering detailed information about the population's distribution, age structure and other characteristics.²³ The Department of Provincial Administration collects and processes registration data from local offices, making it available nationally. Currently, the official statistics registration system is centralized, automated, and fully digitalized with

almost all of the district registration offices being online and collecting and transferring data to the central database in real-time. The registered Thai population statistics are also published by the National Statistics Office in statistical yearbooks. A preliminary examination reveals that average total district population during 2002-2024 for 62 districts ranges from a minimum of 10,515 to a maximum of

213,355 people, highlighting the large coverage between highly urbanized districts and smaller rural areas. It is also noticed that districts within major metropolises and cities have much larger populations than rural districts. 21 districts can be classified as urbanized districts with a total population greater than 100,000 inhabitants.

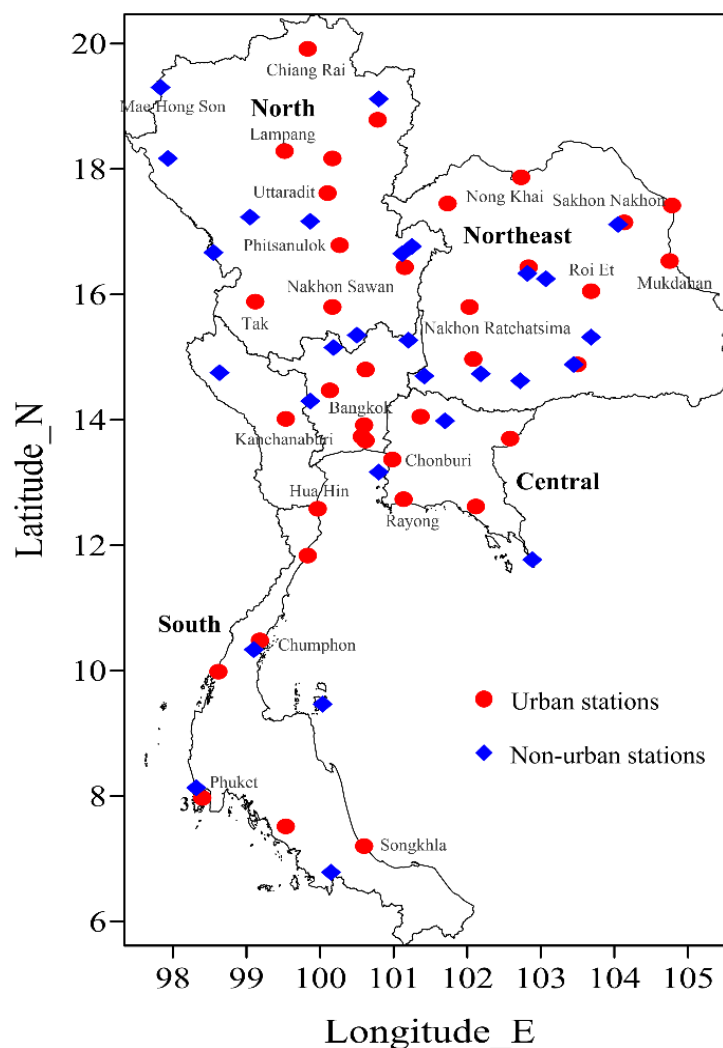


Figure 1. Spatial distribution of the quality-controlled daily minimum and maximum temperature data for the hottest period (March-May) in Thailand during 1970-2024. Each weather station is marked as an urban station or non-urban station based on the classification conducted by Pimonsree et al.¹⁵ and Kachenchart et al.²⁰.

Definition and calculation of hot extremes

The definition of both $T_{\min}$ and $T_{\max}$ -based hot extremes used by most of the previous studies was applied. A hot day (night) is defined as a day when daily $T_{\max}$ ($T_{\min}$) exceeds the 90th percentile of its historical counterparts (1970-2005) for the specific calendar day during the hottest period. The 90th percentiles of $T_{\min}$ and $T_{\max}$ were calculated from multiyear sample units of a 15-day moving window (7 days on either side of this specific day) over the base period (i.e., total samples $15 \times 36 = 540$ days).^{6,8,11,12} This daily-based definition could circumvent the attenuation of the annual cycle of thresholds and the inhomogeneity in calculating percentile-based indices.⁸ On this basis, hot extreme events are divided into three types as follows: 1) IHD – a day with $T_{\max}$ exceeding the 90th percentile with the following $T_{\min}$ lower than the 90th percentile; 2) IHN – a day with $T_{\max}$ lower than the 90th percentile with the following $T_{\min}$ exceeding the 90th percentile; and 3) CHE – a day with both $T_{\max}$ and the following $T_{\min}$ exceeding their corresponding 90th percentiles.^{6,11,12} Three impact-relevant indicators, i.e., frequency, intensity, and duration, are then used to describe the characteristics of hot extremes. For each type of hot extremes, the frequency measures the sum of hot extreme events, while the duration measures the average length of consecutive hot extremes.^{6,11,12} The intensity is calculated as the average magnitude defined as the temperature departure from its corresponding threshold. The CHE intensity was calculated as half of the sum of $T_{\min}$ and $T_{\max}$ minus their corresponding 90 percentiles.^{6,11,12} A linear trend and significance for frequency, intensity and duration of IHD, IHN, and CHE were assessed by a non-parametric Mann-Kendall (MK) test.²⁴ This rank-based method is more statistically robust to the effect of outliers and has been commonly used to detect trends in hydrometeorological

data.²⁴ Maps for station-by-station trends were then made to display spatial distribution. The anomalies relative to the base period from 1970 to 2005 were also used to calculate the whole country time series.

District-level estimation of population exposure to hot extremes

The method of Jones et al.²⁵ was applied to estimate the population exposure to hot extremes. It was calculated by multiplying the number of each type of hot extremes (IHD, IHN, and CHE) by the number of exposed people for both specified base and present periods. As population data records used in this study are relatively short spanning only 23 years, the 5-year interval at the start of data record from 2002 to 2006 was selected as the base period to compare with the present period (2020-2024) at the end of data record. A 13-year interval between two periods is long enough to observe any changes in population exposure. To minimize year-to-year variations, the 5-year average number of each type of hot extremes and total district population were then used in the calculation of exposure. Changes in population exposure can be further decomposed into three effects (climate, population, and their interaction) and each effect's relative importance can be calculated using the decomposition equation (1).^{21,22,26}

$$\Delta PE = (PI * \Delta C) + (CI * \Delta P) + (\Delta C * \Delta P) \quad (1)$$

where ΔPE is the total change in present population exposure, CI and PI are the frequency of hot extremes and population in 2002–2006, and ΔC and ΔP are the changes in hot extremes and population from 2002-2006 to 2020–2024. The $(CI * \Delta P)$ term refers to the population effect measured by allowing the population to change while keeping the climate constant at the base period level. Similarly, the $(PI * \Delta C)$ term denotes the climate effect

calculated by allowing climate to change but holding population fixed at the base period level. The compounding effects of both $(\Delta C * \Delta P)$ represent the result of simultaneous changes in both climate and population, and are defined as the total exposure change minus the summation of climate and population effect changes. An estimate of the percentage change for each indicator can be further derived by dividing both sides of the equation (1) with PEI^{21} as:

$$\frac{\Delta PE}{PEI} = \frac{(P_1 * \Delta C) + (C_1 * \Delta P) + (\Delta C * \Delta P)}{C_1 * P_1} = \frac{\Delta C}{C_1} + \frac{\Delta P}{P_1} + \frac{\Delta C}{C_1} * \frac{\Delta P}{P_1} \quad (2)$$

where PEI is the exposure in 2002–2006 such that $PEI = C_1 * P_1$, $\frac{\Delta C}{C_1}$ and $\frac{\Delta P}{P_1}$ are the percentage changes for climate and population from 2002–2006 to 2020–2024.

RESULTS AND DISCUSSION

Changes of hot extremes in Thailand during 1970-2024

Over the past 55 years, hot extremes during the hottest period in Thailand exhibited notable changes. Analysis reveals a mixture of increasing and decreasing trends in IHD with less significance and more spatial heterogeneity. In particular, 21.5%, 20%, and 6% of the stations recorded significantly positive trends in their frequency, intensity, and duration, respectively (Figure 2). By contrast, all aspects of IHN were dominated by positive trends (Figure 3). The significant rising trends in frequency, intensity, and duration of IHN were observed at 48 (73.8%), 36 (55.4%), and 42 (64.6%) stations, respectively (Figure 3). The three southernmost stations were marked by noticeably increased IHN frequency

(Figure 3). These results are consistent with the study of Limsakul¹³, which found more pronounced increases in annual hot nights than annual hot days in Thailand during 1955-2018. Such disproportionate increase results primarily from mean T_{min} shifted to a high value at a faster rate than mean T_{max} .¹⁴ Our analysis provides additional evidence of widespread and coherent increase not only in the frequency of hot nights as previously documented,^{13,14} but also in their intensity and duration. Similar to IHN, an overwhelming majority of the stations (>90%) registered increases in three indicators of CHE, with more than 50% of the stations recording significantly positive trends (Figure 4). The stations with positively significant trends are prevalent in the South, Central, and Northeast regions, while the remarkably high magnitude of CHE frequency occurred at the Phuket Island station located along the coast of the Andaman Sea (Figure 4). The average rates of the significantly increasing trends in frequency (0.38 events decade⁻¹), intensity (0.07°C decade⁻¹), and duration (0.17 days decade⁻¹) of CHE were comparable to those of IHN. Among the three types of hot extremes, CHE shows the largest number of stations recording positive trends, suggesting that with more hot days and hot nights under the past-to-present shift in mean T_{min} and T_{max} , CHE inevitably increases as the independent events would more likely become connected. These results highlight that Thailand experienced more frequent, prolonged, and more intense IHN and CHE events. Increases in hot nights and compound hot extremes similar to those observed in this study have been observed across most global stations,⁸ across most of the mid-latitudes,⁶ and in South China.¹¹

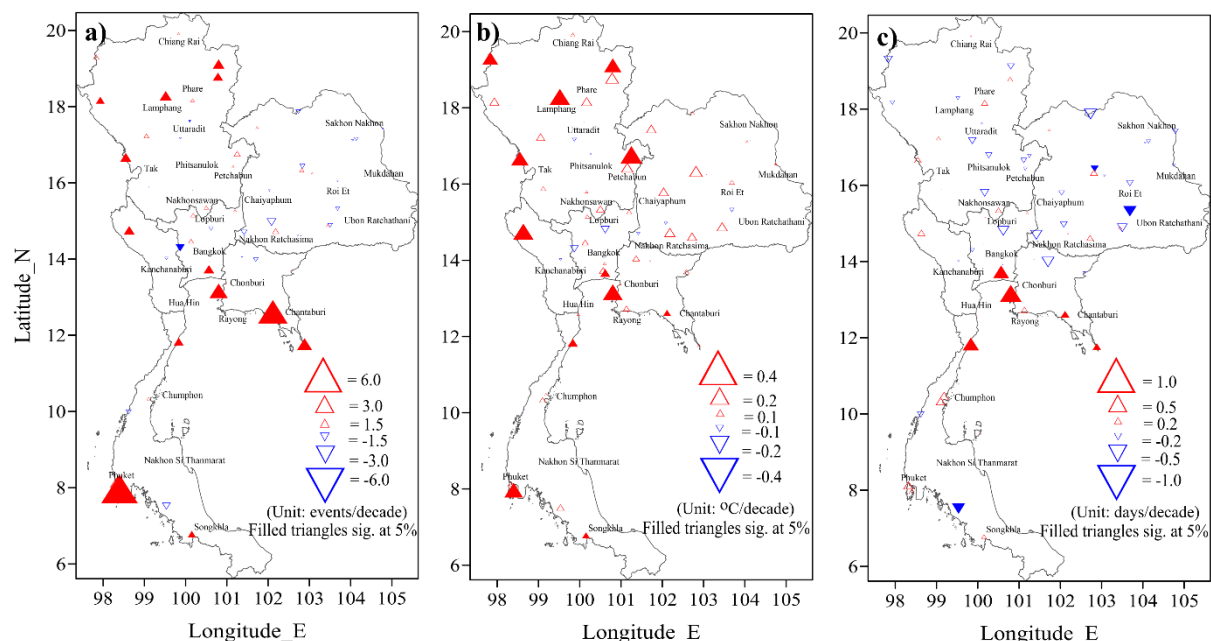


Figure 2. Station-by-station trends in frequency (a), intensity (b), and duration (c) of hot-season (March-May) independent hot days (IHD) in Thailand during 1970-2024. Red and blue triangle symbols represent increasing and decreasing trends, respectively, with filled ones denoting significant changes at the 95% confidence level.

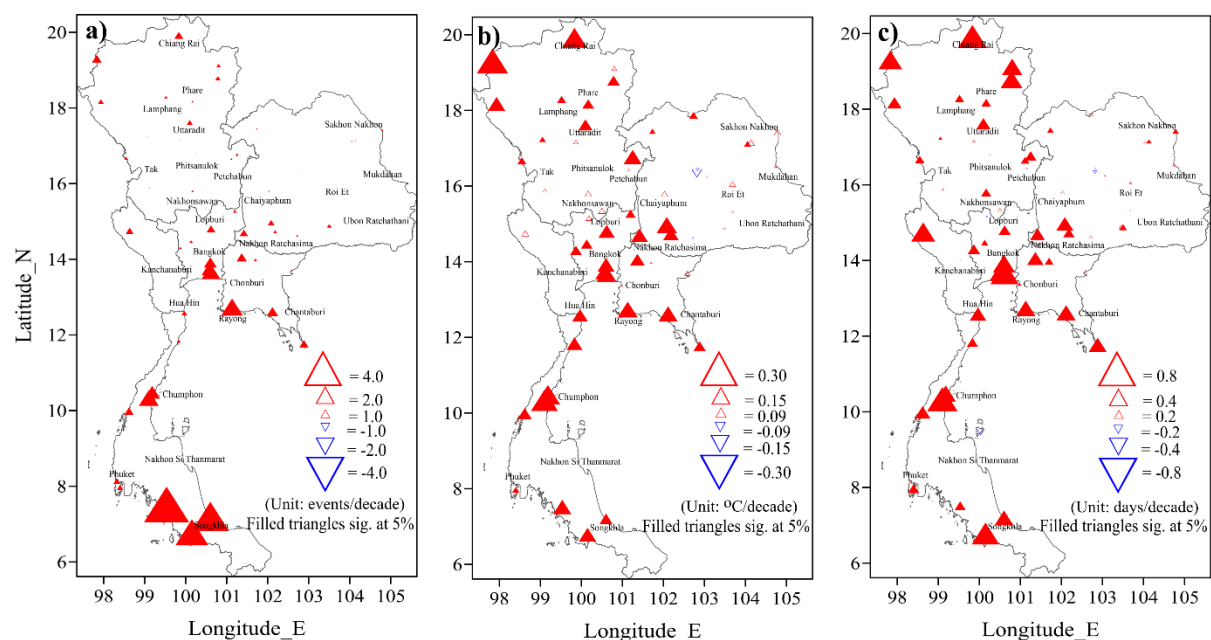


Figure 3. Same as Fig.2 but for independent hot nights (IHN).

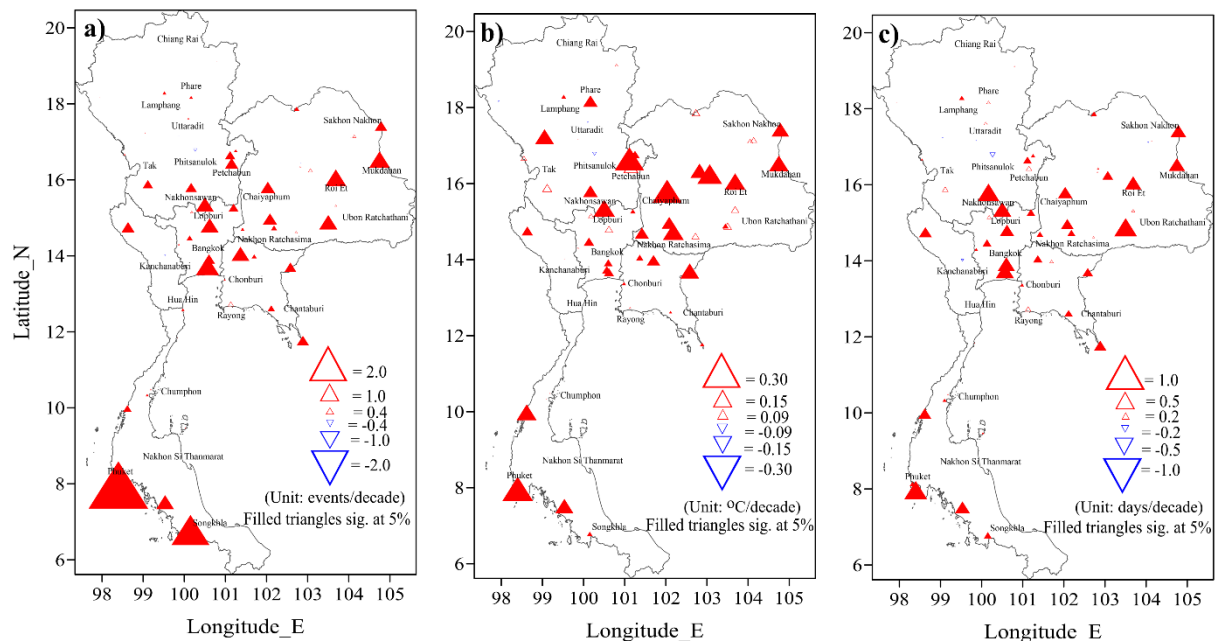


Figure 4. Same as Fig.2 but for compound hot extremes (CHE).

When considering Thailand as a whole, all-station averaged anomalies of IHD did not display any significant trends for the period from 1970 to 2024 but did show large interannual variations, owing to strong cancellation of trends with opposing signs and similar magnitudes (Figure 5a-c). In contrast, those of three characteristics of IHN and CHE for the whole of Thailand exhibited significantly rising trends at the 99% level of confidence (Figure 5d-i). By comparison, all-station averaged anomalies of IHN show stronger trends than those of CHE (Figure 5d-i). It is noted that trends in all-station averaged anomalies of three indicators of IHN and CHE during 2000-2024 were nearly double compared with those during 1970-2024. This feature suggests that increases in frequency, intensity, and duration of IHN and CHE in Thailand have tended to accelerate in recent years, consistent with a step-up in warming rate of global surface temperature post 2000.^{27,28} Evidence shows that global mean surface temperature between the first

decade and second decade of the 21st century increased two times²⁷. Moreover, the 2011-2020 decade was known as the warmest on record for the global land and oceans²⁹. It is an established fact that this accelerated global warming generally leads to a higher rate of recent changes in hot extremes as observed here.³⁰

In addition to consistency with an accelerated warming background, some previous studies show that large changes in land use patterns, especially rapid urbanization, substantially contribute to greater nighttime warming in Thailand through altering local-scale natural surface processes, near-surface heat, momentum, and hydrological balances.^{14,15,31} Larger and significant increases in T_{min} -related indices observed in Thailand during 1970-2019 were mainly attributed to urban heat island intensity, which was more prominently enhanced during nighttime than during daytime.¹⁵ For increased CHEs, multiple factors were elaborated for possible mechanisms. For example, the

increased frequency of CHEs at the global scale resulting primarily from the general warming of boreal summer was shown by Wang et al.⁶ In addition, a rise of CHEs was theoretically and experimentally illustrated to be associated with an increase in regional anticyclonic circulations which facilitate greater adiabatic heating and more absorbed solar radiation. These conditions bring higher $T_{\max}$ and store more heat near the surface, thus partly offsetting the nighttime radiative cooling and elevating $T_{\min}$.^{6, 32} Soil dryness has also been often proposed as an important driver for both daytime and nighttime hot extremes, through inducing evapotranspiration.³³ Correlation analysis between precipitation and temperature revealed that increases in CHEs were larger in regions with stronger land–air interactions.⁶ Some studies also show that an anomalously dry, hot, and sinking air movement associated with the intensification and westward extension of the Western North Pacific anticyclone provide a more favorable environment for enhancing hot extremes and heatwave activities in Indochina.^{34,35} Our discussion with available scientific information from global and regional studies provides only a clue to possible factors inducing the observed increase in CHEs in Thailand.

However, to gain more insight into the detailed and complex mechanisms, more studies using detection and attribution approaches based on high-resolution climate data in combination with climate model-based dynamical simulations are inevitably needed.

To further investigate any changes in hot-extreme types, proportions of each hot-extreme type to total of all hot extremes were computed following the methods of Chen and Zhai¹¹ and Liao et al.¹² Station-by-station trends in proportions of each type in total hot extremes demonstrate significant shifts, behaving as nighttime-accentuated events manifested by increasing IHN and CHE (Figure 6a-c). Specifically, type transition from decreasing IHD towards increasing IHN and CHE occurred at a number of stations (39 and 33 stations out of 65 stations, respectively) especially those located in the Central, Northeast, and South regions (Figure 6a-c). A significant shift from a gradual decline in IHD to the dominance by increasing IHN and CHE was also apparent for the whole country's series (Figure 6d). This observed transition is similar to what was reported in mid-lower reaches of the Yangtze River, northern China, and southern China.¹¹

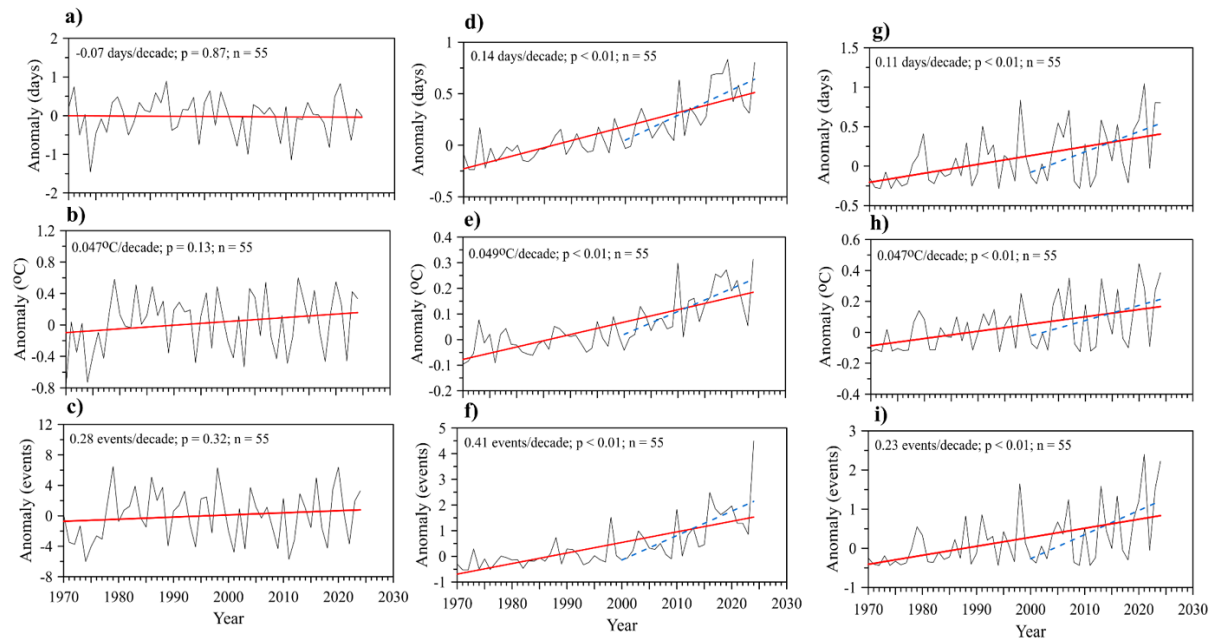


Figure 5. All-station average anomalies and trends in duration (a,d,g), intensity (b,e,h), and frequency (c,f,i) of hot-season (March-May) IHD (left column), IHN (middle column) and CHE (right column) in Thailand during 1970-2024. Note that the dash blue lines represent the trends estimated for the period 2000-2024 ($n = 25$) for d ($0.25 \text{ days decade}^{-1}$; $p = 0.01$), e ($0.090^\circ\text{C decade}^{-1}$; $p = 0.01$), f ($0.95 \text{ events decade}^{-1}$; $p = 0.01$), g ($0.26 \text{ days decade}^{-1}$; $p = 0.01$), h ($0.098^\circ\text{C decade}^{-1}$; $p = 0.05$), and i ($0.62 \text{ events decade}^{-1}$; $p = 0.01$).

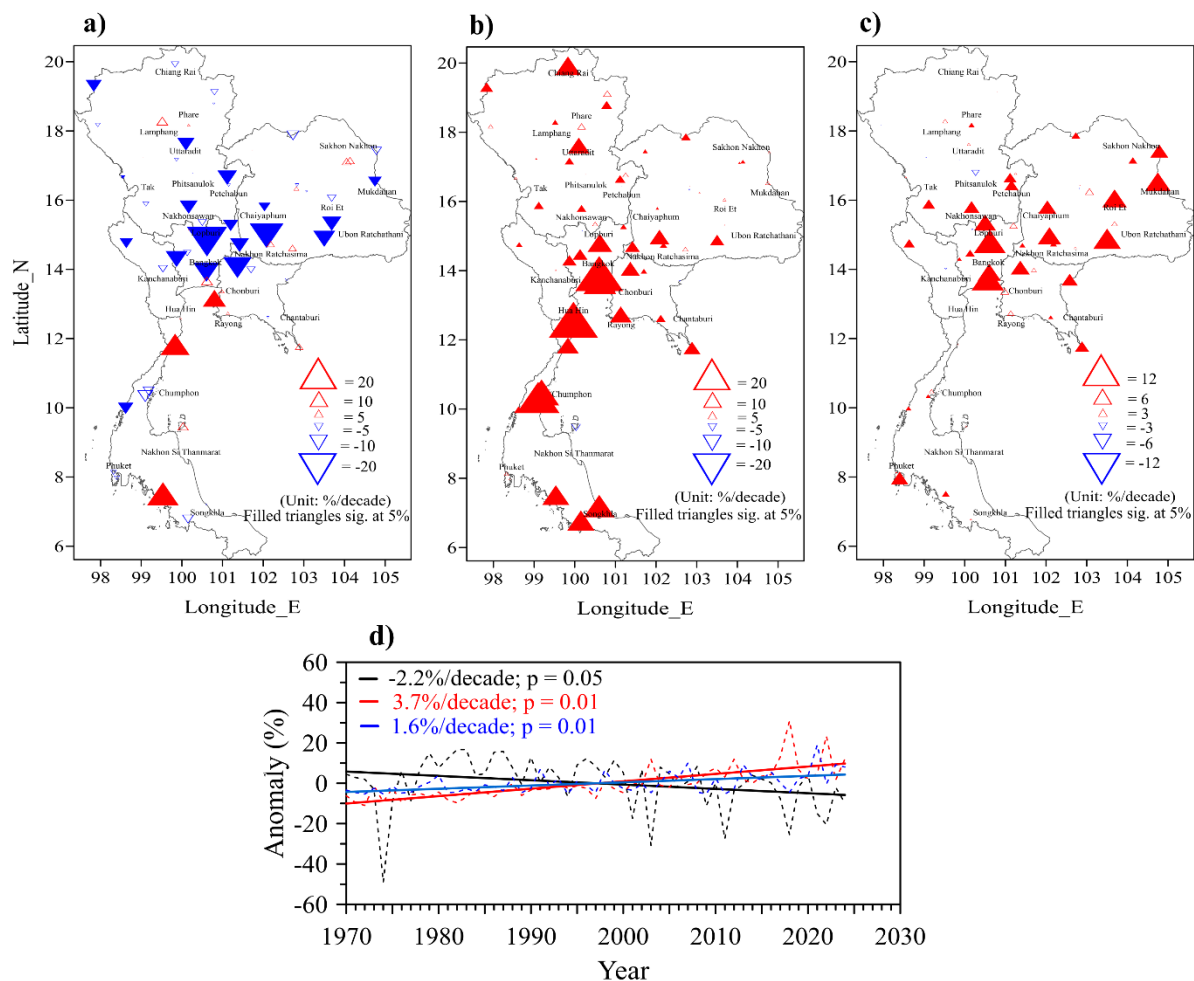


Figure 6. Station-by-station trends in proportions of IHD (a), IHN (b), and CHE (c) in total hot extremes in Thailand during 1970-2024, and all-station average anomalies and trends in proportions of IHD independent hot days (black dash line), IHN independent hot nights (red dash line), and CHE compound hot events (blue dash line) (d) in total hot extremes. The number of total hot extremes at each station is calculated by summing all types of hot extremes (IHD+IHN+CHE).

Estimation of district-level population exposure to hot extremes

Percentage change of estimated population exposure to IHD, IHN, and CHE for the 2020-2024 period relative to the 2002-2006 period at 62 districts where the selected weather stations are located show a spatially distinct distribution ranging from -52.4% to 903.8%, -65.5% to 824.0% and -100.0% to 1096.0%, respectively (Figure 7). Population exposure to IHD between the two periods slightly increased (25 districts) across the selected 62

districts, with an exceptionally high value only occurring at one district in the Central region, which primarily resulted from a large increase in IHD frequency (Figure 7). However, a number of districts experienced noticeably larger magnitudes of increased exposure to IHN and CHE (Figure 7). Increases in population exposure to IHN and CHE were found in 48 and 46 districts, with greater than 100% being in 27 and 26 districts, respectively. The districts in the Central and Northeast were marked by notably higher increases in population

exposure to IHD and CHE. The largest increase in population exposure to CHE

occurred in one district in the Eastern region (Figure 7).

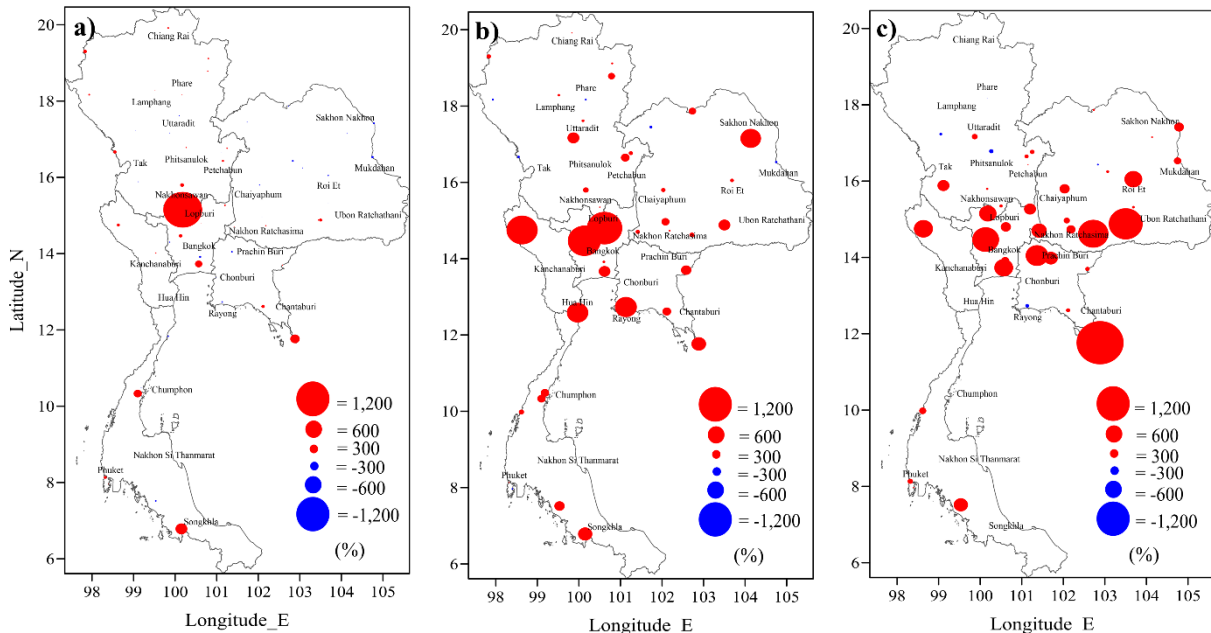


Figure 7. Percentage changes of total population exposure to IHD (a), IHN (b), and CHE (c) for the 2020-2024 period relative to the 2002-2006 period across the 62 districts where the selected weather stations are located.

For all 62 districts, population between the 2002-2006 and 2020-2024 periods declined slightly on average by -1.9%. Meanwhile, all types of hot extremes exhibited large increases between the two periods, especially IHN (183.7%) and CHE (237.1%). As a result of the opposite changes, the all-district sums show that the highest number of people exposed to IHN (8,441,176 person-events) which increased nearly two times its 2002-2006 value. The total population exposure to CHE was estimated to be 6,268,727 person-events, exhibiting a second increase to 146% relative to the base period. The largest population exposure to IHN can be attributed to the increased frequency of IHN during 2020-2024. This nighttime-accentuated increase also leads to higher population exposure to CHE. On the other hand, the exposure of the Thai population to IHD (3,695,891 person-events) during

2020-2024 was much smaller than that of IHN and CHE, equivalent to an increase of only 9% from its base value. Our analysis indicates the increasing tendency for Thai people in the selected 62 districts to experience greater exposure to IHN and CHE than IHD in recent years.

The total sums of the relative effect factors in population exposure to IHD, IHN, and CHE in the selected 62 districts demonstrate that the climatic effect was the predominant driver of the total population exposure to all types of hot extremes (Figure 8). Its contribution increased to 182% (6,743,398 person-events), 99.8% (7,407,825 person-events), and 118.2% (8,424,238 person-events) for IHD, IHN, and CHE, respectively. This analysis highlights that even in the absence of population increases, changing temperatures by themselves greatly amplified the exposure rates to hot

extremes in the selected districts. Our results are consistent with the recent study of Sun et al.⁹ showing that the climate effect is a strong determinant of increased population exposure in most Southeast Asian regions. The climatic effect as the predominant driver for the increases in present-to-future exposure to climate events, similar to this study, was also reported in Europe, mid-to-high-latitude

countries, and China.^{21,26} In contrast, the confounding effect negatively contributed to all types of hot extremes accounting for -52.5% (IHD), -1.5% (IHN), and -12.4% (CHE) of total exposure. Mixed effects can be seen for the population factor which negatively contributed to total population exposure to IHD and CHE but positively affected the total exposure to IHN.

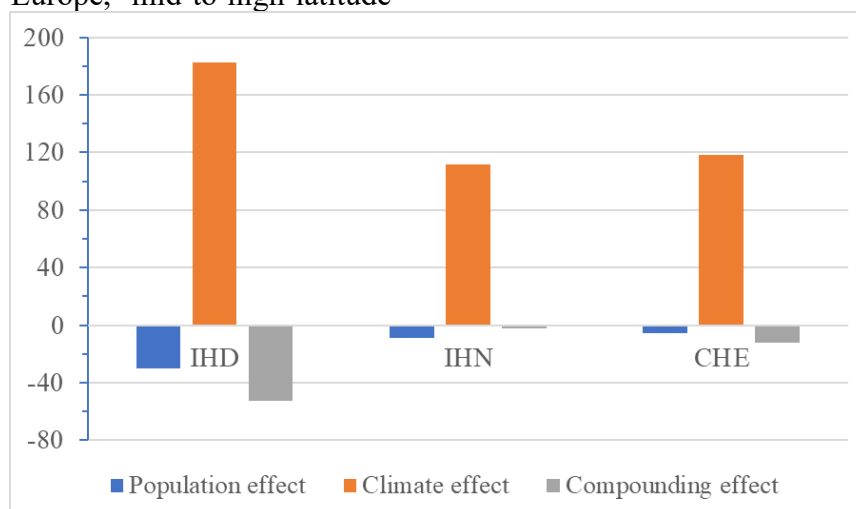


Figure 8. Relative decomposition (%) of the 2020-2024 total population exposure to independent hot days (IHD), independent hot nights (IHN), and compound hot extremes (CHE) relative to the 2002-2006 period into population, climate, and compounding effects for the selected 62 districts.

Recent studies have demonstrated that an increase in consecutive hot periods without nighttime heat relief has important implications for human health, as physiological responses acclimatized to the conventional hot day-cool night mode seem to have been severely disturbed and have subsequently triggered failure in body thermoregulation.^{1,7,8} Continuous exposure to sustained periods of hot extremes deprives people of the opportunity to recover from the ensuing and preceding daytime and nighttime heat, aggravating health conditions and causing lethal cardiovascular and respiratory diseases.^{1,36} Yang et al.¹ show that increasing mortality risks of compound hot extremes, especially for female and older urban residents, are much higher than those occurring solely in the daytime or nighttime. For Thailand,

studies illustrate that an increased risk of mortality was associated with exposure to high temperatures with extreme heat accounting for about 1% of the total mortality during 1999-2018.^{37,38} Moreover, 10% increase in mortality related to respiratory and circulatory systems was linked to exposure to heat events.³⁹ However, more analysis based on epidemiological data related to heat in combination with demographic and socioeconomic data such as age, gender, education level, and income can shed more light on mortality and morbidity risks resulting from exposure to the observed increase in CHE.

CONCLUSION

Based on a bivariate classification scheme for three overlapping types of hot extremes during the hottest months for the period 1970-2024, this study illustrates that Thailand experienced more frequent, prolonged, and more intense IHN and CHE. Their frequency, intensity and duration tended to accelerate in recent years, consistent with a step-up in the warming rate of global surface temperature post 2000. Another associated change with the nighttime-accentuated events is that hot-extreme types in Thailand as a whole shifted from a gradual decline in IHD to the dominance of increasing IHN and CHE. The results also show that, from 2002 to 2024, total population exposure to IHN and CHE at the selected 62 districts especially those situated in the Central and Northeast of Thailand increased by more than 145% relative to the base period. The change in exposure to hot extremes was mainly caused by climatic effects, highlighting that increased hot extremes by themselves substantially escalating population exposure in the selected districts. These results have implications for considering to incorporate population data into risk and exposure analysis of hot extremes in Thailand rather than relying solely on climate data, in order to contribute more scientific understanding and to enhance policy relevance. Continuous exposure to sustained periods of hot extremes may pose larger health risks in the coming years, as Thailand's transition to an ageing society is ongoing and accelerating. This study provides scientific information essential for climate-related risk assessment that is a prerequisite for developing effective adaptation measures to hot extremes. However, additional studies based on available high-resolution gridded population and climate projections in combination with epidemiological data

related to heat and, demographic and socioeconomic data, are needed to expand this study. Their results will provide a full picture of changes in different types of hot extremes and how the whole Thai population could be exposed to them in the future.

AUTHOR CONTRIBUTIONS

WP: Data Curation, Writing - Original Draft and Writing - Review & Editing. AL: Data Curation, Writing - Original Draft and Writing - Review & Editing. NA: Formal analysis. JS: Data Curation, Writing - Original Draft and Writing - Review & Editing. RS: Data Curation. TA: Formal analysis. LW: Formal analysis and Writing - Original Draft.

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CONFLICT-OF-INTEREST STATEMENT

The authors declare that they have no conflict of interest.

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