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Variability of heatwaves across Vietnam in recent decades

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ABSTRACT

There have been several studies on heatwaves (HW) in Vietnam but they all focused on an individual heatwave characteristic. A comprehensive understanding of heat waves is crucial for effective research on their impacts and for making plans for climate change mitigation and adaptation strategies in the country. This study investigates the spatial variability and changing trends in heatwave characteristics across the climatic sub-regions of Vietnam. The analysis is based on the observed daily maximum temperature (Tx) recorded at 144 meteorological stations in the period of 1980-2018. HW is identified using a relative threshold, which is the local 90^{th} percentile of Tx within 183 days during the summer (1^{st} April - 30^{th} September). Results showed that: (1) The threshold values used to determine HW events varied among sub-regions and stations due to their geographical locations; (2) Across the country, HWs were observed to be more frequent, intense, severe, and longer-lasting in the North Delta and North Central sub-regions compared to others; (3) Over recent decades, both the frequency and severity of HWs have significantly increased across Vietnam, particularly in the North-Delta and North Central sub-regions. However, the changing trends in HW duration and intensity remain unclear.

Keywords: Heatwaves, Vietnam, trend, local threshold.

1. Introduction

Heatwaves are among the extreme weather events causing the most harmful consequences for a variety of aspects such as human health. Many studies have shown that extreme heat events increase the risk of heat-related death in many parts of the world, e.g. Europe (D'Ippoliti et al., 2010; Le Tertre et al., 2006), United States (Peterson et al., 2013; Zanobetti & Schwartz, 2008), Australia (Loughnan, et al., 2010; Tong et al., 2010). For example, the heatwave in August 2003 was the worst natural disaster of the last 50 years in Europe, estimated to kill around 70,000 persons (Coumou & Rahmstorf, 2012). In fact, HW is a silent killer (Loughnan et al., 2013) that is responsible for more deaths than recorded, because it impacts on humans gradually and is hard to investigate (Kim et al., 2016). Moreover, HW occurrence is associated with violent behaviors and mental health problems of humans (Anderson, 1989; Hansen et al., 2008). Besides, HW is found to put a major risk to agriculture and food security as it can cause crop disturbances or failures (Niu et al., 2014; Teskey et al., 2014). There is evidence that many parts of the world

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have experienced an increase in HW's frequency, duration, and intensity since the 1950s (Perkins et al., 2012; Perkins & Alexander, 2013; Trancoso et al., 2020). To the last decades, many mega heat waves with long duration and high intensity occurred in several areas, consisting of Europe (2003) (Andrea de Bono, 2004), Russia (2010) (Russo et al., 2015), South Asia (2015) (NOAA, 2015), Southeast Asia (2016) (Thirumalai et al., 2017), etc… Due to the continuing anthropogenic impact on the global climate, it was projected that HW will be more frequent, longer, and more intense in this century through different greenhouse gas emission scenarios (Fischer & Schär, 2010; Trancoso et al., 2020; Alexander & Arblaster, 2012). This can result in highly potential effects of HW on numerous sectors for the next decades.

Although there is a plethora of studies highlighting the severe consequences of HW in various aspects (Andersen et al., 2005; Dole et al., 2011; Lesk et al., 2016), there is currently no universally accepted definition of HW. A heatwave is commonly defined as a period of consecutive days with abnormally high temperatures (Croitoru et al., 2016; Perkins et al., 2012) that have significant impacts on both humans and the ecosystem. Particularly, HW can be defined when the temperature (mean, maximum, minimum, or combination) reaches the given threshold for a period of time. There is a wide range of temperature indicators applied for HW definition, including maximum temperature (Tx), minimum temperature (Tm), mean temperature (Tmean), apparent temperature (Ta), heat index (HI), and excess heat factor (EHF), etc. For example, while some studies used only Tx (Meehl & Tebaldi, 2004; Fischer & Schär, 2010) or Tm (Meehl & Tebaldi, 2004; Fischer & Schär, 2010) or Tmean (Anderson & Bell, 2009), others combined Tx (Ta) with Tm (Nairn et al., 2009) or with Tmean (Yang et al., 2013) to define HW. Among the indicators used, Vaneckova et al. (2011), and Chen et al. (2015) suggested that using Tmean has more advantages than Tx and Tm in projecting mortality as it presents temperature within a day. Other authors preferred Tm than Tx indicator because they found its important role in the mortality rate of the elderly in urban areas (Laaidi et al., 2012). Schifano et al. (2009), D'Ippoliti et al. (2010) believed that Ta, which is combined temperature with humidity, could reflect the effect of HW on human health better than other indicators. However, Barnett et al. (2010) declared that no HW indicator is better than others when employing numerous HW indicators to predict deaths in US cities.

HW can be defined based on absolute or relative thresholds. For example, for absolute threshold-based criteria, a variety of Tx values were used to identify HW, for example, 30°C (Hutter et al., 2007), 32°C (Hertel et al., 2009), 35°C (Huang et al., 2010; Tong et al., 2010; Sun et al., 2014), 37°C (Tong et al., 2010), etc. Meanwhile, relative thresholds, which are percentile-based values, were applied widely for HW definition, such as the 90^{th} percentile of Tx (Fischer & Schär, 2010; Perkins et al., 2012; Russo et al., 2015), Tm (Perkins et al., 2012; Panda et al., 2017; Piticar, 2018) and maximum Ta (Oudin Åström et al., 2015); the 90^{th} (Tong et al., 2014), 97^{th} (Anderson & Bell, 2009), 99^{th} (Anderson & Bell, 2009) percentile of Tmean. Besides, in several studies, HW was also defined by a combination of relative and absolute thresholds. For instance, in Yang et al. (2013) HW was identified in a certain period when Tx $\geq$35°C and Tmean $\geq 98^{th}$ percentile. In short, the definition of HW is diverse, depending on the practical and scientific aspects to be concerned about.

According to IPCC (2013), Vietnam is expected to be one of the most vulnerable countries to climate change (IPCC 2013). The average temperature in Vietnam has been increasing at a rate of 0.26±0.1°C per decade during the period of 1971-2010, which is twice the rate of global warming (Nguyen et al., 2013). Projections indicate that in the mid- and late-21st century, the temperatures are expected to rise by 1.2-1.7°C and 1.6-2.4°C, respectively, based on the low emission climate change scenario RCP 4.5 (MONRE, 2020). In 2019, according to the Centre for Hydro-Meteorological Forecasting, several stations recorded exceptionally high temperatures, including Son La (42.2°C), Tuong Duong (42.4°C), Huong Khe (43.4°C), among others. HW is one of the most serious extreme events occurring frequently almost all around the country in the summer, especially in the Northern and Central areas.

However, there is limited research on heatwaves in the country, with existing studies mainly focusing on one characteristic of HW, which is hot days. As a result, a study by Ngo & Bui, (2023) examining hot and cold extreme events revealed an increase in the number of the hot days and severe hot days in the northern regions of Vietnam from 1961 to 2018 (Ngo & Bui, 2023) Furthermore, a projection based on RegCM3 model suggests that the number of hot summer days is expected to continue increasing until 2050 in all climatic sub-regions of the country, with a 5-9% increase compared to the 1980-1999 period (Ho et al., 2011).

Therefore, further research on HW is necessary to address the existing gaps in the scientific literature and provide a comprehensive understanding of HWs in Vietnam. Such research would contribute to the development of effective plans and strategies to cope with this climatic event and its potential impacts. This study aims to investigate and understand the spatial variability of key HW characteristics and their changing trends in recent decades across the entire Vietnam. To the best of our knowledge, no similar study has been conducted to date, highlighting the novelty and significance of this research endeavor.

2. Data and methods

2.1. Study area

Located in the eastern Indochina peninsula, Vietnam has a tropical climate and is affected by the Asian monsoon systems: northeasterly monsoon in the winter (November to April) and southwesterly monsoon in the summer (May to October). The mainland of Vietnam is stretched in the north-south direction with a long coastline of more than 3,200 km. Due to the complex topography with high mountain ranges whose directions are almost orthogonal to the prevailing wind, such as, Hoang Lien Son in the north and Truong Son along the west border, the climate of Vietnam is divided into seven sub-regions (Nguyen Duc Ngu & Nguyen Trong Hieu, 2013): Northwestern (R1), Northeastern (R2), North Delta (R3), North Central (R4), South Central (R5), Central Highlands (R6), and the South (R7) (Fig. 1). The rainy season in the R1-R3 and R6-R7 is coincident with the summer monsoon, from May to October, while it shifts to the autumn-winter, from August to December in the R4-R5 sub-regions (Nguyen Duc Ngu & Nguyen Trong Hieu, 2013). In the wintertime, due to the cold surge activity, the temperature is quite low over the R1-R4 sub-regions. The lowest temperature sometimes drops to below 0°C along with snow and frost fall in the mountainous areas (Nguyen Duc Ngu & Nguyen Trong Hieu, 2013). In contrast, temperature during the summertime over the country is very high, especially in the R1-R5 sub-regions, where maximum temperature can reach up to 40-42°C or higher and accompanying intense HW.

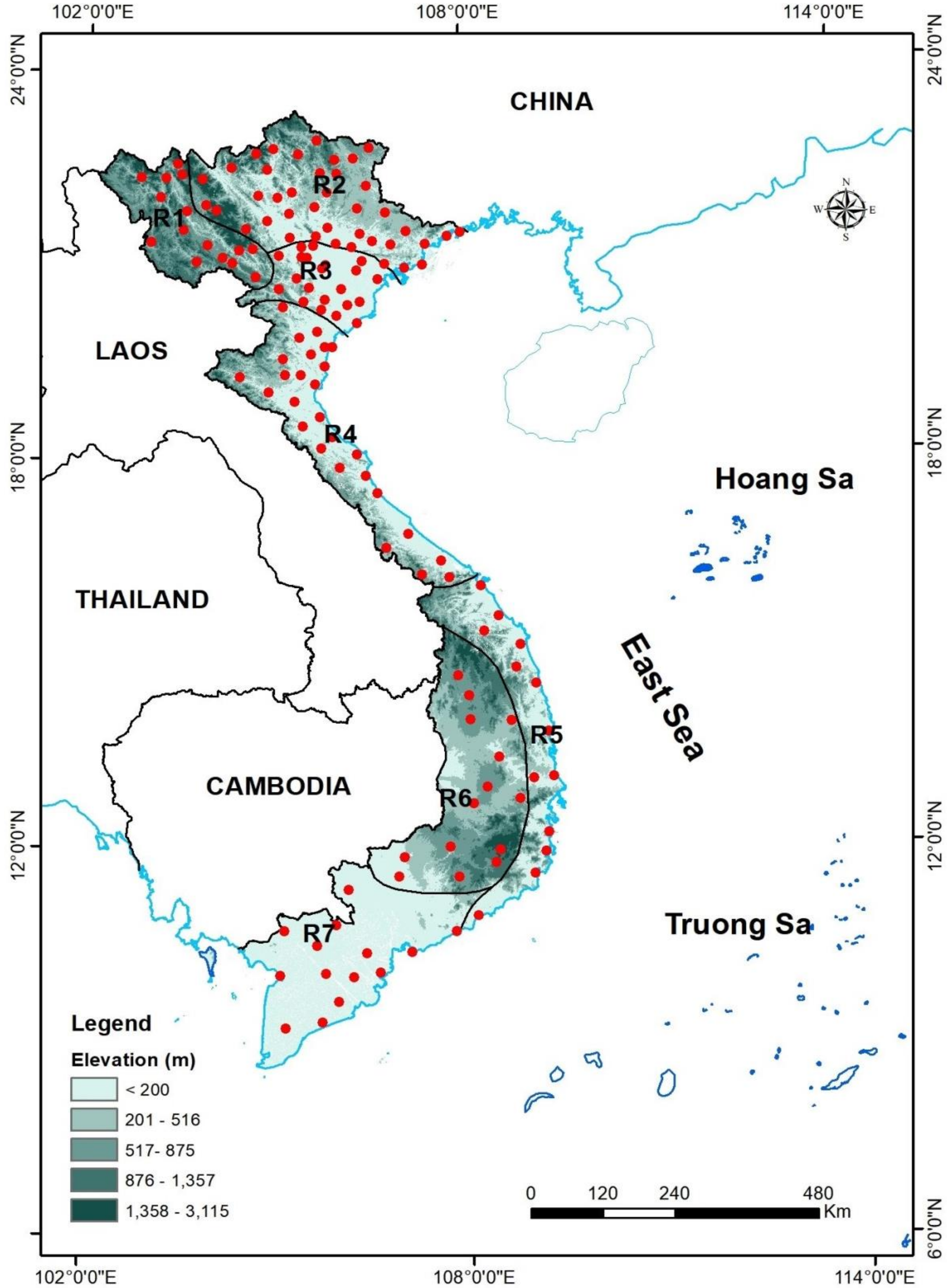

Figure 1. Map of sub-climatic regions and the location of stations in the mainland of Vietnam (R1: Northwest, 14 stations; R2: Northeast, 42 stations; R3: North Delta, 20 stations; R4: North Central, 27 stations; R5: South Central, 13 stations; R6: Central Highland, 14 stations; R7: The South, 14 stations

2.2. Data

This study utilized observed daily maximum temperature (Tx) data from meteorological stations over the mainland of Vietnam. The data covered the period from 1st April to 30th September, totaling 183 days, spanning the years 1980-2018 (39 years). The selection of this time period is based on the fact that daily maximum temperatures during the summer months (April to September) exhibit relatively consistent patterns across the country. To minimize potential biases related to missing data, the following criteria were applied in this study. Only meteorological stations that had no more than 18 missing values corresponding to approximately 10% of the total data were included in the analysis. Additionally, stations with no more than 4 consecutive missing days within the time series data for each year were considered. By adhering to these criteria, a total of 144 stations across the entire country were collected for analysis. The distribution of these stations across the sub-climatic regions is as follows: R1: 14 stations, R2: 42 stations, R3: 20 stations, R4: 27 stations, R5: 13 stations, R6: 14 stations, R7: 14 stations. The geographical distribution of the station network can be visualized in Fig. 1.

2.3. Heatwave definition

As mentioned above, many definitions of HW are used worldwide. In Vietnam, a HW is understood as a hot spell that is determined by an absolute threshold when the daily maximum temperature of at least two consecutive days equals or exceeds 35°C. However, HW can be defined using relative thresholds that have been widely adopted in many parts of the world (Perkins et al., 2012; Russo et al., 2015). The advantage of using the relative thresholds is that they can reflect major consequences of abnormally high temperatures regardless of the fact that climate condition at considered locations is warm or cold, such as low plain areas vs high mountain areas. Therefore, instead of the fixed threshold, in this study we use a relative threshold, determined by the local 90th percentile of Tx, to define HW (Perkins et al., 2012; Perkins & Alexander, 2013; Russo et al., 2015). Particularly, a HW event is identified when the daily Tx of at least 3 consecutive days exceeds the local daily threshold calculated using data from the baseline period 1981-2010 (Russo et al., 2015).

2.4. Heatwave characteristics

In this study the following heatwave characteristics are examined (Fischer & Schär 2010; Perkins & Alexander 2013; Croitoru et al. 2016; Piticar 2018; Panda et al. 2017): (1) Number of HW events (HWN), (2) number of HW days (HWF), (3) number of hot days (HDays), (4) HW duration (HWD), (5) HW amplitude (HWA), (6) HW magnitude (HWM), (7) and HW severity (HWS). The study specifically examined the period from 1st April to 30th September in each year. This timeframe was chosen because it represents the period when the daily maximum temperature (Tx) values demonstrate relative homogeneity across the country.

(1) Number of HW events (HWN): HW is a spell of at least 3 consecutive days with Tx above the daily threshold.

(2) Number of HW days (HWF): Total number of days in all HW events.

Number of hot days (HDays): Total of days with Tx above the daily threshold.

(3) HW duration: The duration of a HW event is the number of consecutive days with Tx above the daily threshold. The mean (maximum) duration of HW [HWDm (HWDx)] is defined as the average (maximum) value of the durations of all HW events.

(4) HW amplitude (HWA): The highest daily Tx in all HW events.

(5) HW magnitude (HWM): The average daily Tx of all HW events.

(6) HW severity: The severity of a HW event is defined as the sum of differences between daily Tx and corresponding daily threshold values. The mean (maximum) severity of HW [HWSm (HWSx)] is the average (maximum) value of all severity of HW events.

HWs were analyzed based on their characteristics, which can be grouped into four categories: (1) HW frequency (HWN, HWF, and Hdays), (2) HW duration (HWDm and HWDx), (3) HW intensity (HWM and HWA), and (4) HW severity (HWSm and HWSx).

By considering these different categories of HW characteristics, the study aimed to comprehensively assess and understand the spatial variability and changing trends of heatwaves in Vietnam.

2.5. Trend analysis

In this study, we apply the nonparametric Mann-Kendall test (Mann, 1945; Kendall, 1970) at a 5% significance level to determine the changing trend of all HW characteristics mentioned in Section 2.3. The magnitude of changing trends is determined by the nonparametric Sen's slope estimator (Sen, 1968). In comparison to parametric methods, the nonparametric methods do not require any assumption on the data distribution and can well handle missing data and outliers (Gocic & Trajkovic, 2014).

3. Results and discussions

3.1. Local daily threshold to determine HW

Figure 2 shows the local daily threshold from 1st April to 30th September of 144 stations over Vietnam, which are defined as the 90th percentiles of maxima temperature centered on a 31-day window for the baseline period 1981-2010. It can be seen that the highest threshold values were in the R3-R5 sub-regions, especially in R4 and R5. During June-August (60th-150th days), the HW thresholds in these sub-regions were much greater than 35°C. This is because during the summertime these sub-regions received the most amount of solar radiation and were influenced by Fohn effects (Nguyen Duc Ngu & Nguyen Trong Hieu, 2013). In contrast, the lowest threshold values were in R6 with less than 30°C during August - September (120th - 180th days) which related to the topographical heights in this sub-region. The threshold values of less than 25°C can also be observed at the high-elevation stations, such as SinHo (1,529 m), SaPa (1,570 m), DaLat (1,509 m),…

In general, during a year, threshold values reached peaks in the mid-summer (June-August) in the R2-R5 sub-regions, while these peaks occurred in April-May over the R1, R6, and R7 sub-regions. The peak of thresholds in April-May over R1 could be associated with the South Asian Heat Low from the west in pre-summer monsoon months, but over R6-R7 these peaks might be attributed to the high solar radiation related to the apparent motion of the sun during the end of the dry season (Nguyen Duc Ngu & Nguyen Trong Hieu, 2013). In addition, the threshold values in R2-R3 in April-May were significantly lower than that in other sub-regions which could also be related to the activity of cold surges in the transitional period from wintertime to summertime, leading to temperature decrease.

3.2. Climatology of HW's characteristics

Figure 3 shows the spatial patterns of HW characteristics during the summertime (1st April to 30th September) for the period 1980-2018 over 144 stations entire Vietnam using local daily thresholds in Fig. 2. In general, the HW characteristics varied from region to region. However, it reveals that these characteristics can be separated into several groups with similar patterns of spatial distribution: (1) HW frequency (HWN, HWF, and Hdays), (2) HW duration (HWDm and HWDx), (3) HW intensity (HWM and HWA), and (4) HW severity (HWSm and HWSx).

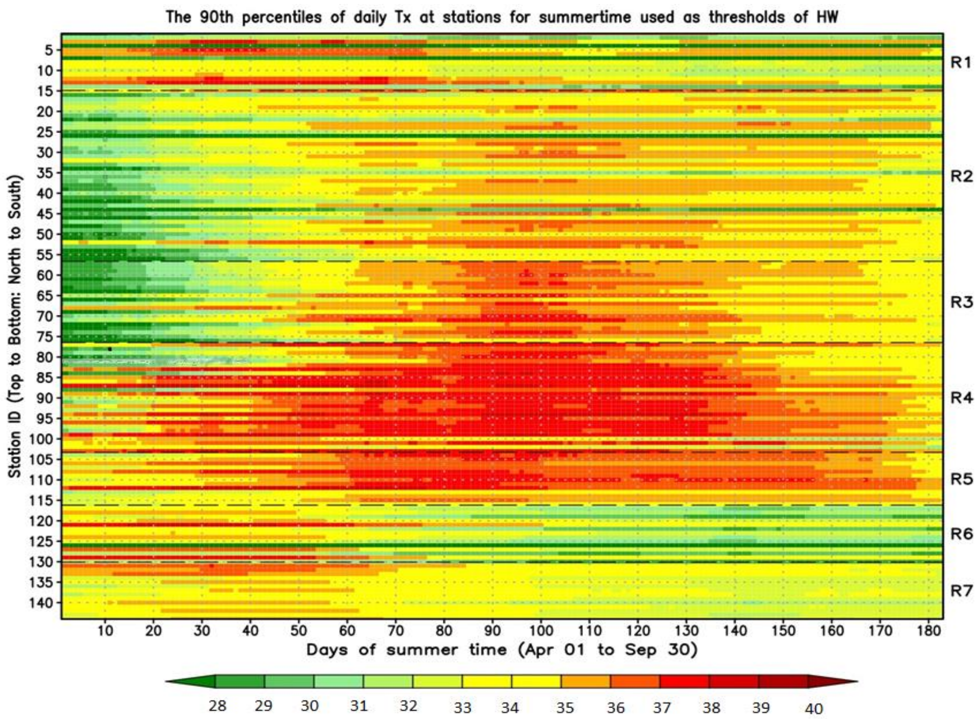

Figure 2. The values of 90^{th} percentile of Tx in all stations from April to September

Figure 3 shows that there was quite a similarity in terms of spatial distribution among a couple of HW characteristics in the same group. Both HW frequency and severity reached the peaks in the R3 sub-region, while HW intensity hit the highest points in the Central sub-regions (R4 and R5) and HW duration came atop in R3 and R7. It implies that over the country the centers of HW were observed in R3 and R4 where HW occurred the most frequently, intensely, severely, and lasted the longest. In contrast, R6 had the lowest frequency and intensity of HW, while R1 had the shortest duration and R7 had the least severity.

Regarding the HW magnitude, Table 1 shows the median of regional mean values of HW characteristics over the period of 1980-2018. It can be seen that R3 experienced the most HW frequency with around 30 hot days, 19 HW days being equivalent to 4 events per year on average. R2 experienced the second-highest frequency of HW, with an average of around 25 hot days, 13 HW days, and a little over 3 events per year. The lowest HW frequency was evident in R6, with around 15 hot days, 7 HW days, and 1.6 events per year. For HW duration, the R7 and R3 were reported the longest with median values of HWDm and HWDx being 4.7 days and 6.6 days for the R7, and 4.5 days and 6.4 days for the R3 respectively. The lowest values of HWDm and HWDx detected in R1 were on average of 4 days and 5 days per year. For intensity, median values of HWM and HWA in the most intense sub-region of HW (R4 and R5) were above 36°C and 37°C, while the values of these characteristics in the least intense sub-region R6 were a little over 32°C and 33°C, respectively. For severity, the highest points of HW severity were in the R3 with 8°C for HWSm and 14.8°C for HWSx. The lowest values of HWSm and HWSx were approximately 3°C and a little over 5°C observed in the R7.

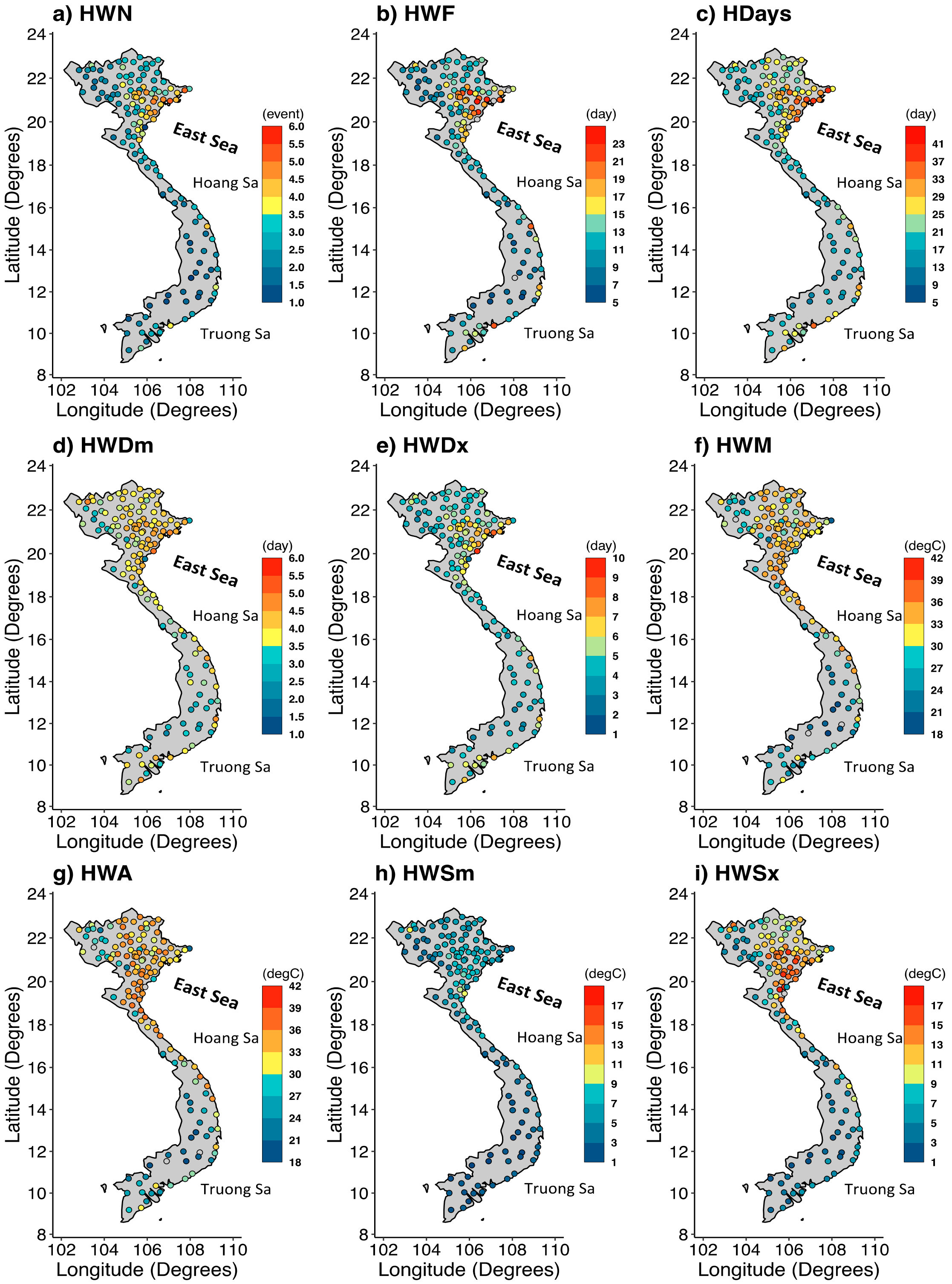

Figure 3. Annual mean values of HW characteristics over the period of 1980-2018 in the summertime

Table 1. Median of regional mean values of HW characteristics

Region	HWN	HWF	Hdays	HWDm	HWDx	HWM	HWA	HWSm	HWSx
R1	2.1	9.1	18.1	4.1	5.0	34.3	34.9	5.0	7.7
R2	3.1	13.1	24.5	4.2	5.3	34.4	35.5	6.6	11.3
R3	4.1	18.5	29.8	4.5	6.4	34.5	35.7	8.0	14.8
R4	2.7	11.7	19.7	4.1	5.5	37.4	38.1	7.0	10.5
R5	2.6	11.4	23.1	4.4	6.0	36.4	37.3	4.9	8.5
R6	1.6	7.4	15.1	4.5	5.6	32.5	33.1	3.3	5.2
R7	2.4	11.6	21.7	4.7	6.6	34.3	34.7	2.9	5.1

Among the stations analyzed, the highest values for various HW characteristics were observed in specific regions: (1) HW frequency: Bai Chay station (R2) had the highest HW frequency with 5.3 events and 26.3 HW days. Van Ly station (R3) also had a high HW frequency with 4.9 events and 36.1 hot days; (2) HW duration: Van Ly station (R3) exhibited the longest HW duration, with an average duration of 5.7 days (HWDm) and a maximum duration of 10.5 days (HWDx); (3) HW intensity: The highest HW intensity values were recorded in Tuong Duong station (R4), reaching 39.3°C for Heatwave Magnitude (HWM) and 40.1°C for Heatwave Amplitude (HWA); and 4) HW severity: Tinh Gia station (R4) showed the highest HW severity values, with an average severity of 10.6°C (HWSm) and a maximum severity of 19.1°C (HWSx).

These stations, located in the southern regions of R2, R3, and the northern region of R4, exhibited the most extreme values for the respective HW characteristics.

3.3. Trend of changes in HWs characteristics

Figure 4 presents the changing trends of HW characteristics during the summertime for the period of 1980-2018 over 144 stations in the mainland of Vietnam.

Generally, an increasing trend was observed for all HW characteristics, especially in the R3 and R4 sub-regions. Among the HW characteristics, frequency and severity exhibited the most significant increase. It can be observed that the trend of HW intensity is small, even unchanged or slightly decreasing, but does not meet the 5% significance level.

Table 2 presents the median values of changes in HW characteristics over a 39-year period. In general, the median values of changes were positive for most regions, indicating an overall increasing trend. However, negative values were observed for HW intensity in R1 and R7. One notable finding is that the median values in R3 were the highest among all sub-regions for HW frequency, duration, intensity, and severity. For example, the medians of changes per decade in R3 were 0.83 events for HW frequency (HWN) and 4.47 days for HW days. Similarly, R3 had median values of 0.92°C for HW severity (HWSm) and 3.21°C for HW severity (HWSx). Furthermore, R7 exhibited the highest median values of changing rates for Hdays (6.07 days per decade) and HWDx (0.83 days per decade), indicating significant changes in HW duration in that region. These findings highlight regional variations in the magnitude of changes in HW characteristics, with R3 showing the highest median values for multiple characteristics and R7 exhibiting notable changes in HW duration.

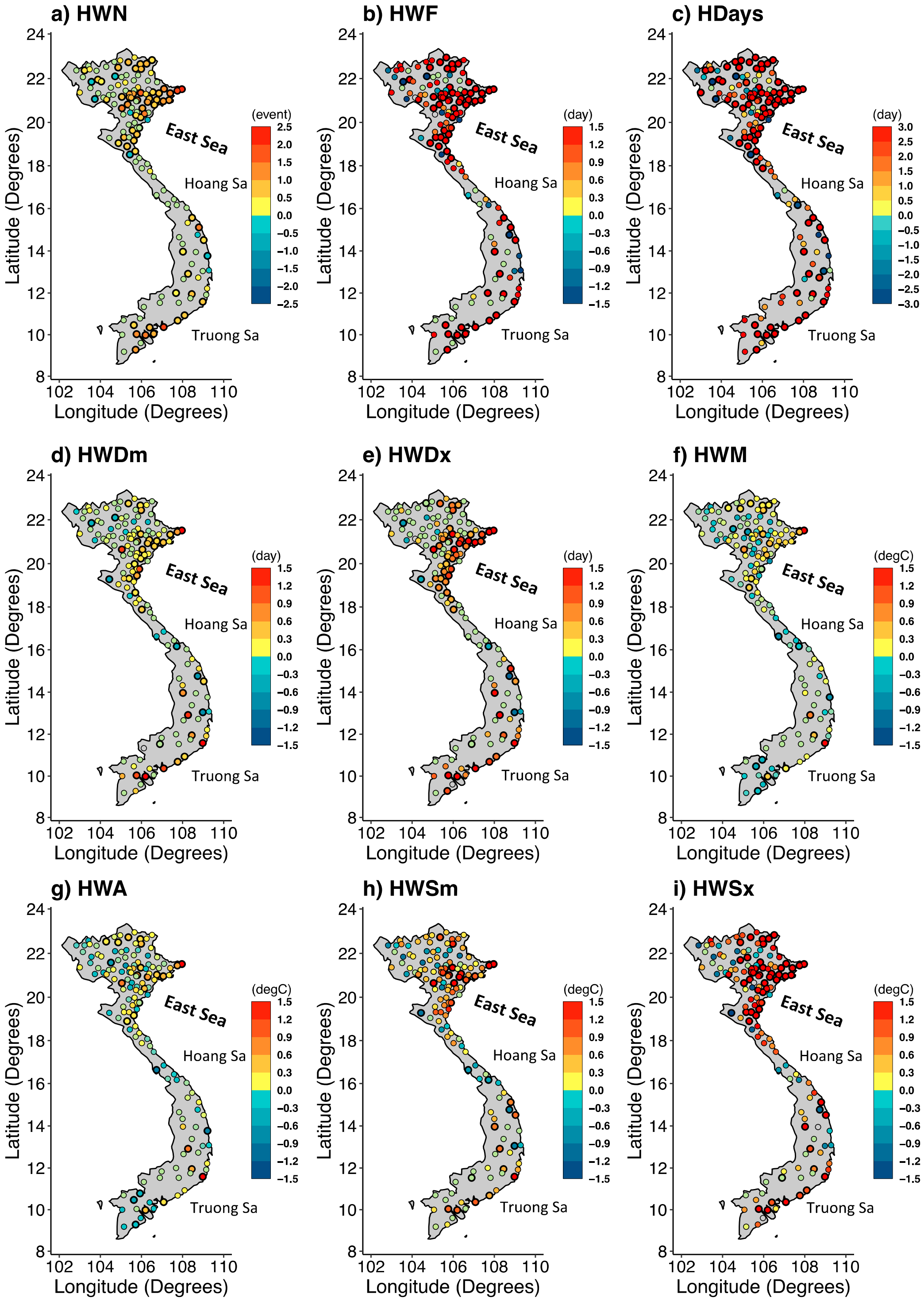

Figure 4. Trend of changes of HW characteristics over the period of 1980-2018 calculated by the nonparametric Mann-Kendall test. Dots with outer bold black circle are satisfied 5% significant levels

Table 2. Median of changing values of HW characteristics

Unit: changes/decade

Region	HWN	HWF	Hdays	HWDm	HWDx	HWM	HWA	HWS	HWSx
R1	0.00	0.91	2.41*	0.00	0.00	-0.04	-0.08	0.06	0.07
R2	0.50	2.48*	3.51*	0.00	0.00	0.12	0.10	0.40	1.43
R3	**0.83***	**4.47***	4.88*	**0.20**	0.74*	**0.21**	**0.23**	**0.92**	**3.21***
R4	0.00	1.56	2.31*	0.18	0.37*	0.00	0.00	0.25	1.05
R5	0.33*	2.86	3.75*	0.16	0.42*	0.06	0.05	0.28	0.85
R6	0.00	0.15	2.32	0.00	0.00	0.00	0.00	0.07	0.40
R7	0.62*	3.54*	**6.07***	0.18	**0.83**	-0.12	-0.18	0.14	0.69

*represents at least 50% of stations of the sub-region with trend satisfied 5% significant level

Looking in more detail at Fig. 4, it is apparent that the frequency of HW has significantly increased, with a maximum rise of 2.2 events/decade for HWN, 17 days/decade for Hdays, and 10 days/decade for HW days in Mong Cai station. The increase of HW severity was up to 2°C (6.5°C) per decade for HWSm (HWSx) in Ha Noi and Hiep Hoa stations. Briefly, over the entire Vietnam HW has significantly increased in recent decades, characterized by a strong upward trend of HW frequency and HW severity, especially in the R3 and R4 sub-regions. Also, R3 exhibited a statistically significant increase for almost characteristics of HW. A smaller increasing trend was also seen for the HW duration and intensity. However, at some stations, there is no significant evidence of a changing trend or a slight decrease (at the 5% level) in HW duration and intensity (Fig. 4 and Table 2).

4. Conclusions

Heat waves are frequent extreme weather events in Vietnam and have significant impacts on both humans and the ecosystem. To effectively study the impacts of heatwaves and develop strategies to cope with this kind of event, it is crucial to conduct comprehensive research on heat waves. However, most existing studies in Vietnam have focused on analyzing hot days, which is just one characteristic of heatwave.

This study aims to fill the gap in the literature by investigating the spatial variability and trends of key HW characteristics across Vietnam. Daily maximum temperature data from 144 meteorological stations covering the period 1980-2018 were utilized for this analysis. The HW events were identified based on the local daily thresholds during the summertime from 1st April to 30th September of the year. The study findings revealed the following key points:

(1) The threshold values used to determine heatwave events varied significantly across climatic sub-regions and stations, depending on factors such as season and geographical location. This indicates that using the local thresholds is essential as they can differ significantly from fixed thresholds.

(2) On average, Vietnam experiences approximately 3-4 HW events per year, with each event lasting around 4-6 days. The R3 and R4 sub-regions had the highest frequency of HW occurrences, along with the highest severity and longest duration. Additionally, while the number of hot days (Hdays) exceeded the number of HW days (HWF), they exhibited similar spatial patterns.

(3) Overall, there has been an increasing trend in HW characteristics throughout the country in recent decades. HW frequency (HWN, HWF, and Hdays) and severity (HWS and HWSx) showed the most significant increases, particularly in the R3, R4, and R7 sub-regions. The trends for HW duration (HWDm and HWDx) and intensity (HWM and HWA) were less clear, with some stations

showing no change or even a decrease, although these changes did not reach statistical significance at the 5% level.

It is important to note that this study did not investigate the underlying reasons for the observed results. Future research should focus on exploring the mechanisms driving these findings. Nonetheless, this study provides valuable insights into the spatial variability and trends of heatwave characteristics in Vietnam, laying the foundation for further investigation and the development of effective heatwave management strategies.

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