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Spatial Distribution and Trends of Heat Stress in Vietnam

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ABSTRACT

This study investigated the spatial distribution and trend of heat stress in Vietnam using data from 68 meteorological stations between 1979 and 2018. Daily maximum wet-bulb temperature (TWmax), an indicator of heat stress, was computed based on the daily maximum air temperature (Tx) and relative humidity at 13:00 LST (RH13). The results indicate a strong positive correlation (>0.72) between daily TWmax and Tx and a weak relationship between daily TWmax and RH13. Tx and TWmax generally increased across most stations over the study period, while RH13 displayed both negative and positive trends. The heat stress thresholds for each station are defined using the 95th percentile values of TWmax during the baseline period 1979-1998. We found that most parts of Vietnam experienced an increase in heat stress days, with the interquartile range across all stations spanning from 0.8 to 4.2 days per decade. Among seasons, summer contributed the most (typically 52-80%) to the annual number of heat stress days in most sub-regions, except for the Central Highlands and the South, where spring contributed the most (44% and 41%, respectively). Overall, this study provides useful benchmark values for future research on heat stress in Vietnam.

1. INTRODUCTION

Climate change affects human health, well-being, livelihoods, and various aspects of society in multiple ways, from increasing the risk of extreme events to increasing the risk of infectious diseases. Biologically, the human body regulates its internal temperature by maintaining a delicate balance between hot and cold temperatures. However, when exposed to excessive heat, the body's ability to regulate its temperature is compromised, resulting in adverse effects on human health (Petkova et al., 2013). Both hotter and colder temperatures have been associated with an increased risk of death and disease (Perkins, 2015; Glaser et al., 2016). The Intergovernmental Panel on Climate Change's (IPCC) special report on 1.5°C global warming (Hoegh-Guldberg et al., 2018) reported a global increase in heat stress due to surface heating, which exacerbates exposure and vulnerability to climate-related stress (Cramer et al., 2014). The topic of heat stress has attracted considerable attention and research efforts in recent decades. Some studies have focused solely on temperature data (e.g., Dong et al., 2015; Liu et al., 2017; Harrington and Otto, 2018), while others have also employed humidity besides temperature due to its critical role in heat stress discomfort (e.g., Matthews et al., 2017; Mora et al., 2017; Coffel et al., 2018).

Vietnam, located in the tropical monsoon region of Southeast Asia, is among the countries most affected by climate change (MONRE, 2012; Vu Duy et al., 2022). Temperatures in Vietnam have increased by approximately 0.78ºC from 1981 to 2018, which is equivalent to about 0.21ºC per decade (Espagne et al., 2021). It is noteworthy that even moderate shifts in mean temperatures can significantly change the risk of extreme events (Arias et al., 2021). Thus, a seemingly moderate increase of 0.78ºC in mean temperatures in Vietnam can dramatically elevate the frequency of

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extremes, including heat stress, occurring in the country. To date, there have been no specific studies on the changes in heat stress in response to the temperature increase across Vietnam, except for some studies focusing on local impacts. For instance, Opitz-Stapleton et al. (2016) analyzed trends in day and night temperatures from 1970-2011 and examined several heat indices to determine the degree of heat stress among workers in Danang. Their findings suggested that nighttime temperatures were excessively high after hot days, preventing workers from recovering and leading to heat stress. Dang et al. (2019) focused on the association of temperature with mortality and hospitalization in Ho Chi Minh City. They found that heat waves significantly increase the risk of death in the elderly and people with respiratory disease.

To address the gap in the literature outlined above, this study examined the relationship between temperature, relative humidity, and heat stress in Vietnam. Specifically, the study addressed two questions: (1) How do temperature and relative humidity interact to affect heat stress in Vietnam? (2) How has heat stress in Vietnam changed over the past four decades in response to the increase in temperature, and what is the spatial distribution of these changes? The remainder of this paper consists of four sections. In Section 2, we describe the data and methods of analysis utilized in our study. Sections 3 and 4 present the results obtained from the analysis and the associated discussion, respectively. Finally, the study's conclusions are presented in Section 5.

2. METHODOLOGY

2.1 Station data

The daily maximum temperature (Tx) and daily relative humidity at 13:00 LT (RH13) during the period 1979-2018 at 68 meteorological stations of the Vietnam Meteorological Hydrological Administration (VNMHA) were used in this study (Figure 1, Table S1). We analyzed the changes over the seven climatic sub-regions of Vietnam: Northwest (N1), Northeast (N2), North Delta (N3), North Central (N4), South Central (S1), Central Highlands (S2), and South (S3). These climatic sub-regions were identified based on radiation, temperature, and rainfall characteristics (Nguyen and Nguyen, 2004) and have been widely used in climate studies of Vietnam (Phan et al., 2009; Ngo-Duc et al., 2014; Le et al., 2019).

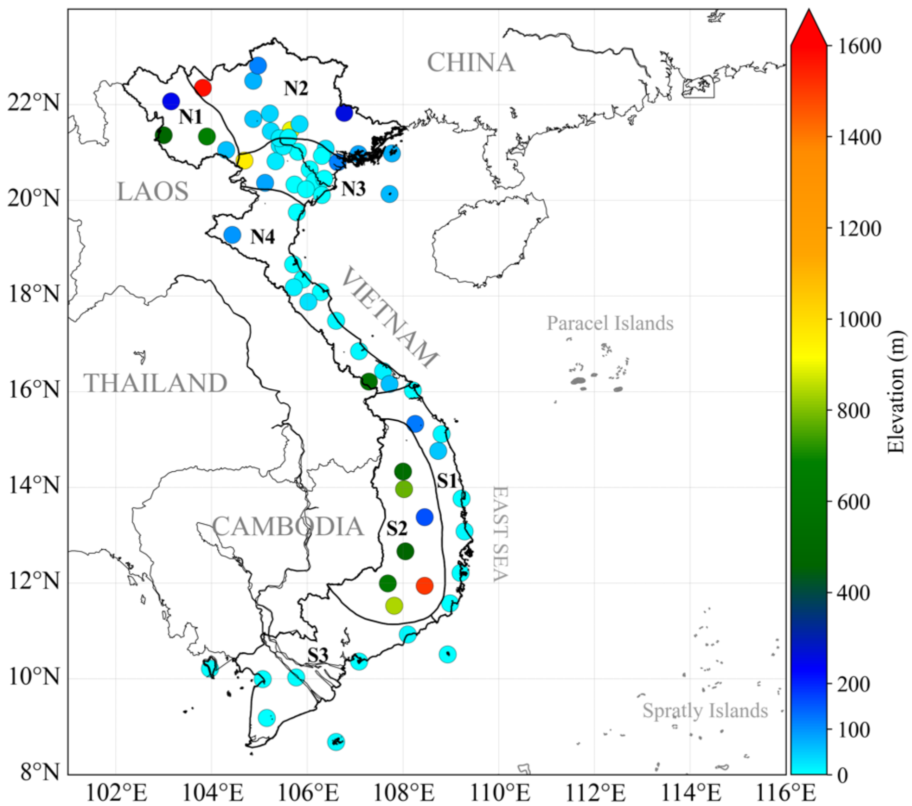

Figure 1. Locations of the 68 meteorological stations (blue-filled circles) used in the study and the seven climatic sub-regions of Vietnam

2.2 Daily maximum wet-bulb temperature

Various heat stress indicators have been developed to quantify the level of heat danger. Most indicators use air temperature and relative humidity as inputs (Morabito et al., 2014; Coffel et al., 2018; Wang and Zhu, 2020). Here we utilized the daily maximum wet-bulb temperature (TWmax) index to represent extreme heat stress. Unlike other indices, TWmax establishes a clear thermodynamic limit on heat transfer that cannot be offset by adaptations (Davies-Jones, 2008; Pal and Eltahir, 2016; Im et al., 2017). Higher values of TWmax imply hot and humid conditions while lower values indicate less extreme conditions. We estimated the TWmax index using a mathematical formulation based on daily Tx and RH13, as shown below (Stull, 2011):

$$\begin{aligned}\mathrm{TWmax} = \ & \mathrm{Tx} \times \mathrm{atan}\left[0.151977 \times (\mathrm{RH13\%} + 8.313659)^{\frac{1}{2}}\right] \\ & + \mathrm{atan}(\mathrm{Tx} + \mathrm{RH13\%}) - \mathrm{atan}(\mathrm{RH13\%} - 1.676331) \\ & + 0.00391838 \times (\mathrm{RH13\%})^{\frac{3}{2}} \times \mathrm{atan}(0.023101 \times \\ & \mathrm{RH13\%}) - 4.686035\end{aligned} \quad (1)$$

Where; the arctangent function (atan) uses argument values as if they are in radians.

It is important to note that TWmax is best estimated when Tx is reached around 13:00 local time (LT), the same time as the RH13 measurement. Since hourly station data are not available, we used the hourly 2m-temperature (T2m) data of the ERA5-land reanalysis (Muñoz-Sabater et al., 2021) for the summer months of June, July, and August (JJA) in 2019. The data were used to estimate the difference between hourly T2m and the daily average T2m at each latitude band in Vietnam (see supplementary Figure S1). The analysis confirmed that Tx is generally reached around 13:00 LT across Vietnam. Therefore, combining Tx and RH13 to compute TWmax was a reasonable choice for our study.

2.3 Heat stress criteria

The health impacts of heat vary considerably depending on population demographics, acclimation, socioeconomic status, physical activities, clothing, and other factors. As such, the threshold for heat stress is merely an approximation (Kjellstrom et al., 2009; Spector and Sheffield, 2014; Xiao et al., 2015). To date, there has been no predefined absolute threshold for identifying heat stress using the wet-bulb temperature index (Schwingshackl et al., 2021). The only defined threshold is 35°C, identified as a limit for survivability (Sherwood and Huber, 2010). To account for the fact that human beings acclimate to their environment, percentile values are commonly used instead of absolute quantities (e.g., Meehl and Tebaldi, 2004; Peng et al., 2011; Grundstein et al., 2015). In this study, we defined heat stress thresholds for each local station in Vietnam using the 95th percentile values of TWmax for the baseline period 1979-1998. The 95th percentile allows for capturing the higher end of the TWmax distribution while minimizing the influence of outliers in the data. This choice was based on previous research that suggests that temperatures over the 80th percentile at specific locations can threaten human health (Meehl and Tebaldi, 2004; McMichael et al., 2006; Anderson and Bell, 2011; Peng et al., 2011). Some studies even proposed relative thresholds ranging from the 90th to the 99th percentiles (Robinson, 2001; Hajat et al., 2006; Grundstein et al., 2015). Kang and Eltahir (2018) employed the 95th percentile value of TWmax as a metric to assess the intensity of extreme heatwaves. Using the baseline period of 1979-1998 enabled us to assess how heat stress has changed over the past two decades (1999-2018) compared to the earlier period.

2.4 Seasonal selection and trend analysis

We computed and assessed the characteristics of Tx, RH13, and TWmax for the annual average and for spring (March-April-May, MAM), summer (June-July-August, JJA), autumn (September-October-November, SON), and winter (December-January-February, DJF).

The Sen's method (Sen, 1968) was employed for trend analysis. The statistical significance levels of the Sen's slope were obtained using the nonparametric Mann-Kendall test (Kendall, 1975).

3. RESULTS AND DISCUSSION

3.1 Spatial distribution and trends of Tx, RH13, and TWmax

Figure 2 indicates the spatial distribution and trends of the daily maximum temperature (Tx) in Vietnam. It shows that the annual average of Tx ranges between 19-31.8ºC and generally increases from the North to the South. Annual Tx averages under 25ºC are found in the mountainous areas in the Northwest (N1) (e.g., SaPa Station [103.82ºE, 22.35ºN], 19.0ºC) and Central Highlands (S2) (DaLat Station [108.45ºE, 11.95ºN], 23.3ºC), where temperatures decrease with higher elevation. Annual Tx averages above 31ºC occur at stations in South Central (S1) (e.g., PhanRang Station [108.98ºE, 11.58ºN], 31.8ºC), Central Highlands (S2) (Ayunpa Station [108.45ºE, 13.4ºN], 31.65ºC), and South (S3) (e.g., CaMau Station [105.15ºE, 9.18ºN], 31.7ºC). The distribution of Tx across the seven climatic sub-regions varies by season (Figure 2(b-e)). In DJF, low Tx values of less than 23ºC are found in the Northern regions. In JJA, high Tx values are observed in almost all stations across Vietnam, particularly in the Central Coast regions, where the values reach around 34.5ºC.

An increasing trend of Tx during the analysis period was observed across Vietnam (Figure 2(f-j)). Tx increases over almost all areas of Vietnam, except for QuyNhon Station [109.22ºE, 13.77ºN] in the South Central region and some stations in the Central Highlands with a slight decreasing and non-significant trend. The average increasing trend peaks at 0.32ºC/decade in the North Delta (N3), followed by the South (S3) with an average trend of 0.24ºC/decade, although the trends in the South are not homogeneous among stations. Among seasons, the Tx increases in MAM and SON are highest in the Northern and Southern domains, respectively.

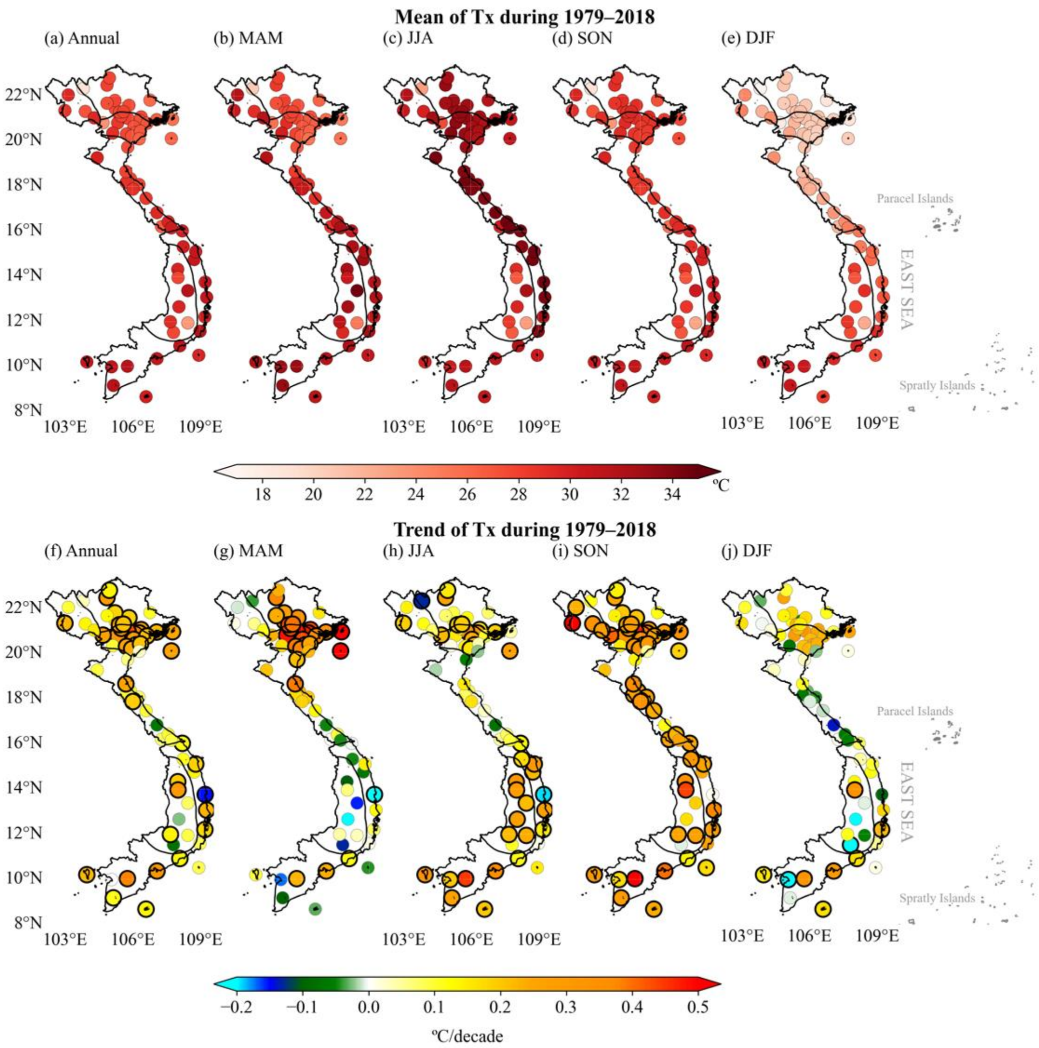

Figure 2. Spatial distributions of the mean (upper panel) and trend (lower panel) of Tx during 1979-2018 for the annual average and the four seasons. The circles with black contours in the lower panel indicate where the trend is statistically significant at the 95% level

Figure 3 shows the spatial distribution of the mean and trend of annual and seasonal averages of relative humidity at 13:00 LST. RH13 values below 60% are found in the Northwest (N1) and Central Highlands (S2) regions. The coastal areas experience more humid conditions with RH13 values above 80%. Similar to Tx, the RH13 values are also seasonally dependent (Figure 3(b-h)). For example, the RH13 values at some stations in the Central Coast are relatively high (>70%) in autumn and winter but low (<60%) in summer. This can be explained by the foehn effect caused by the Truong Son mountain range in the western part of the region.

Unlike Tx, which has increasing trends at almost all stations, RH13 displays both negative and positive trends for the period 1979-2018, varying from -1.63%/decade to 2.23%/decade (Figure 3(f-j)). RH13 decreases by -0.79%/decade in the North Delta region, with the largest decrease of -1.63%/decade at Hanoi Station [105.8ºE, 21.02ºN]. RH13 increases by around 0.25%/decade in the North Central region, reaching up to 2.23 %/decade at Nam Dong Station [107.72ºE, 16.17ºN]. RH13 trends vary by climatic sub-region and season. Significantly decreasing RH13 trends are seen in the North Delta in MAM, the Central Highlands in JJA, and the South region in JJA and SON. Meanwhile, significantly increasing RH13 trends are recorded at some stations in the North Central region in all four seasons and in the Central Highlands in MAM and DJF.

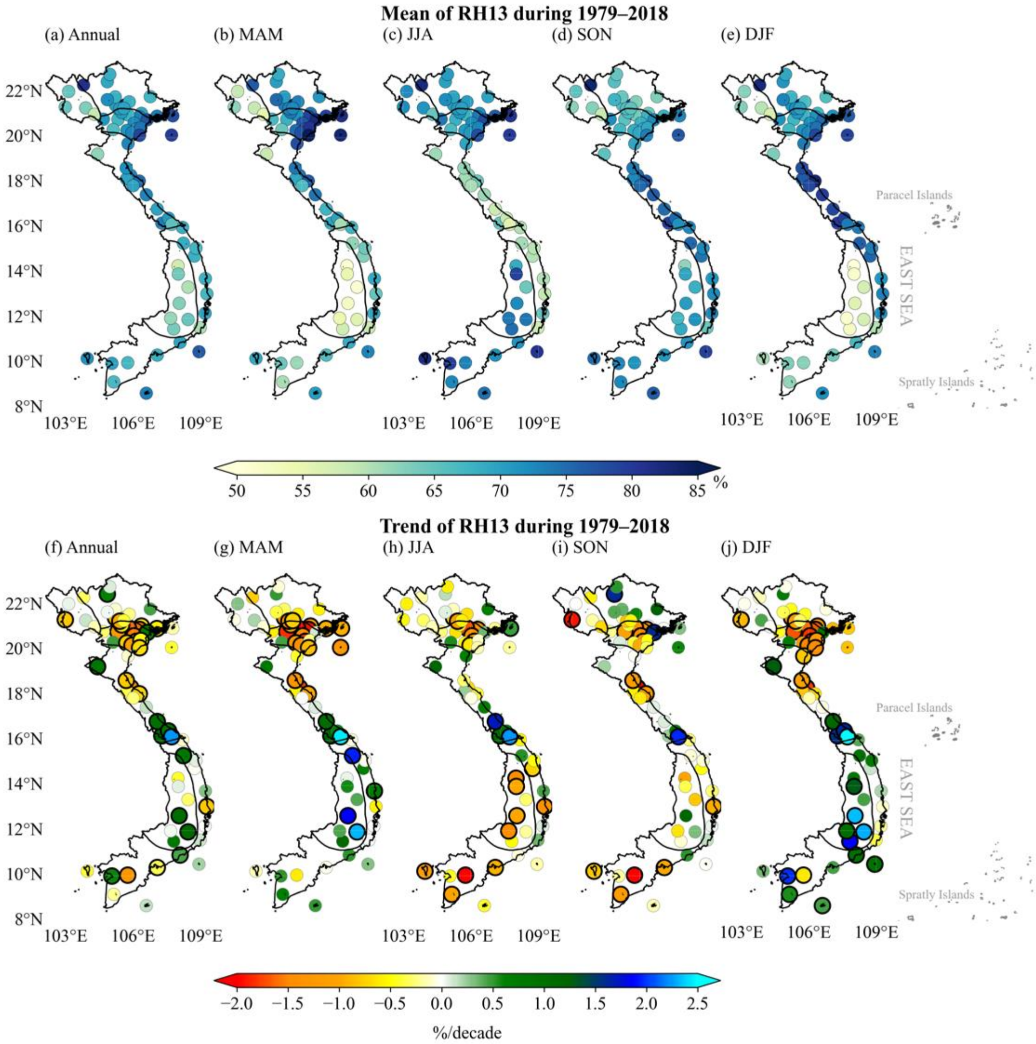

Figure 3. As in Figure 2 except for RH13 rather than for Tx

There are large regional and seasonal variabilities of TWmax across Vietnam (Figure 4). Similar to Tx, the annual TWmax generally increases from the North to the South. TWmax strongly depends on topography, with relatively lower values in the mountainous areas. The lowest annual TWmax of 16.5ºC was recorded at SaPa Station [103.82ºE, 22.35ºN, 1,570 m] in the Northwest; the highest value of 26.6ºC was observed at PhanThiet Station [108.1ºE, 10.93ºN, 9 m] in the South Central region (Figure 4(a)). Concerning seasonal variability, lower TWmax values are generally found in DJF; higher values are recorded in JJA for most sub-regions and in MAM for the Central Highlands and the South. The highest TWmax in JJA of 28.7ºC was measured at PhuLien Station [106.63ºE, 20.8ºN] in the North Delta, while the lowest TWmax in DJF of 11.0ºC was observed at SaPa Station [103.82ºE, 22.35ºN].

Figure 4(f) shows a general significant increasing trend in annual TWmax during 1979-2018.

The trends are more pronounced in the North Delta sub-region than in other sub-regions. Only QuyNhon Station displays a significant decreasing trend of TWmax (of -0.08ºC/decade); this can be explained by the observed downtrend in Tx (Figure 2(f)). Figure 4(g-j) depicts the TWmax trends for each season. TWmax increases most rapidly during MAM in the North Delta (>0.23ºC/decade) and increases significantly in almost all sub-regions during SON. The slightly increasing trends in DJF are not statistically significant at most stations, except for some stations mainly located in the South. In JJA, the increasing TWmax trends, with maximum rates greater than 0.2ºC/decade, are more pronounced in the Central Coast region.

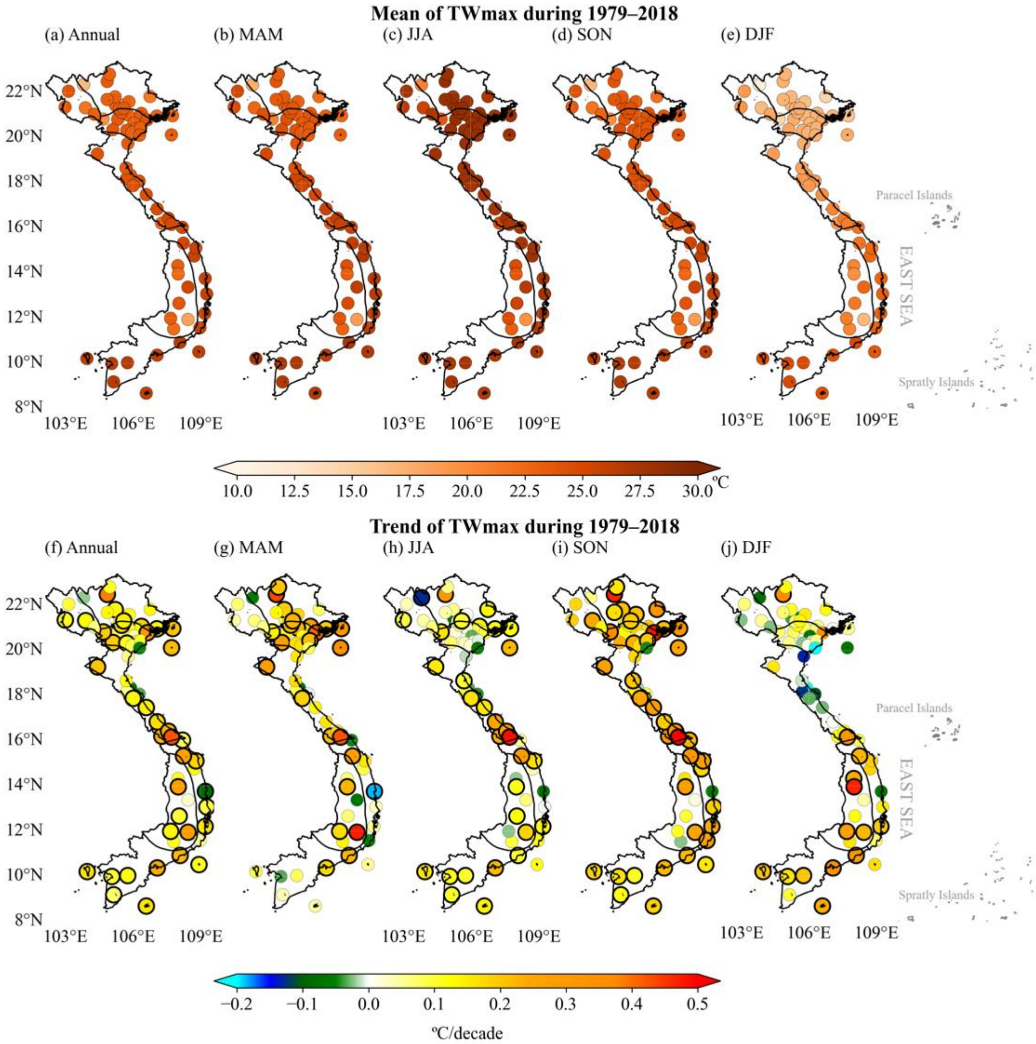

Figure 4. As in Figure 2 except for TWmax rather than for Tx

Since TWmax is calculated from Tx and RH13 (Equation 1), the spatial distribution and trend of TWmax shown in Figure 4 can be interpreted through the values of Tx and RH13. Figure 5 illustrates the relationships between TWmax and the daily Tx and RH13 values of the 68 stations for the period 1979-2018. The results indicate negative correlations between Tx and RH13, e.g., r=-0.72 in summer (Figure 5(a)). These negative correlations can be explained by the capacity of the atmosphere to hold more water vapor in a warmer climate, leading to lower relative humidity. The correlations between TWmax and RH13 are weak: r ranges from -0.05 in summer to 0.24 in autumn. Figure 5(c) demonstrates a robust association between TWmax and Tx, indicating that Tx plays a crucial and more dominant role in determining TWmax, i.e., heat stress, compared to RH13. The results strongly indicate that the seasonality of TWmax is closely tied to the seasonality of Tx, with the highest correlation observed in winter (r=0.9) and the lowest correlation observed in summer (r=0.72).

3.2 Heat stress characteristics and trends

According to the heat stress criteria proposed in Section 2.3, the days with TWmax values exceeding the 95th percentile of the 1979-1998 daily series are considered heat stress days. Figure 6 shows how these 95th percentile thresholds vary across 68 stations in Vietnam. The heat stress threshold is high (≥28ºC) at most stations in the North Delta and Central regions, with the highest recorded value of 29.9ºC at QuyNhon Station [109.22ºE, 13.77ºN]. By contrast, lower heat stress thresholds (≤26ºC) are observed in high-elevation areas, such as in the Northwest and Central Highlands. The lowest heat stress threshold of 21.3ºC is observed at DaLat Station [108.45ºE, 11.95ºN]. In the North Delta region, the typical heat stress thresholds range between 28.8-29.8ºC, while in the South, these values are slightly lower, ranging between 28.0-29.6ºC.

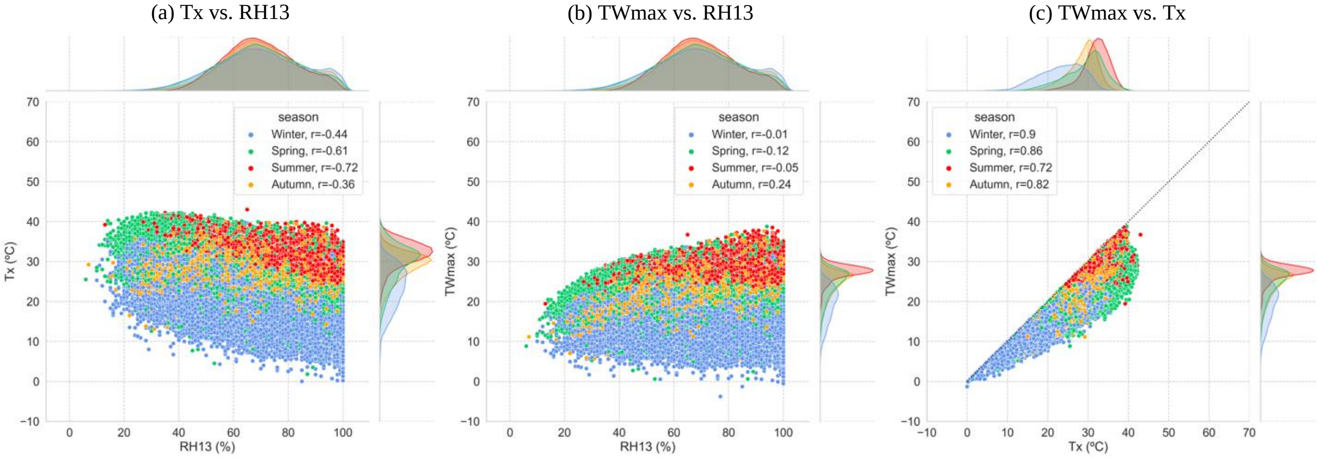

Figure 5. Relationship between (a) Tx and RH13, (b) TWmax and RH13, and (c) TWmax and Tx for the four seasons. The probabilistic distributions for each variable and the Pearson r correlation coefficients for each pair and season are also displayed.

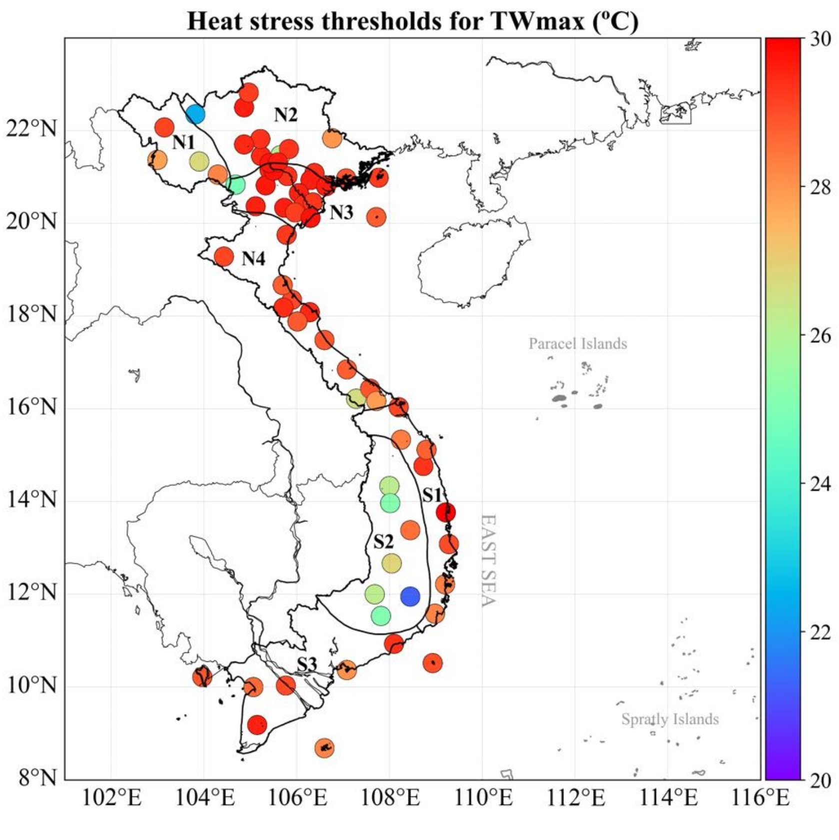

Figure 6. Heat stress thresholds at each station, identified as the 95th percentile value of daily TWmax for the period 1979-1998

Applying the heat stress criteria depicted in Figure 6, the number of heat stress days (DOH) was estimated for each year and each season. While the 95th percentile value of daily TWmax corresponds to about 18 DOH for an average year between 1979 and 1998, Figure 7(a) indicates higher DOH values, generally exceeding 18.5 days per year, for many stations over 1979-2018. Across all stations, NamDong Station [107.72ºE, 160.77ºN] exhibits the highest annual DOH of around 47.8 days, followed by TraMy Station [108.25ºE, 15.33ºN] with 31.7 days. Conversely, the lowest annual DOH values are found in the South Central region, with the minimum of 10.8 days at PhanRang Station [108.98ºE, 11.58ºN].

The annual DOH varies greatly by season, with the largest contribution of JJA found in most regions, except for the Central Highlands and the South. The Northern regions show the highest average JJA contribution to the annual DOH, with percentages of 79.5%, 77.9%, and 67.6% in the Northeast, North Delta, and Northwest, respectively. This is followed by the North Central and South Central regions with contributions of 54.6% and 51.6%, respectively. Meanwhile, the Central Highlands and South regions experience an average JJA contribution of only about 38%.

The average MAM contribution to the annual DOH is approximately 44.4% for the Central Highlands stations, 41.0% for the South stations, and around 36.1% for the stations in the Central regions. In the Northern regions, the average MAM contribution is approximately 22% for the Northwest and only about 13% at Northeast and North Delta stations.

The SON contribution to the annual DOH is relatively small, ranging from 3.7 to 25.2% for all stations. For DJF, the contribution to the annual DOH is negligible (mostly <1%) for most regions of Vietnam, except for the South region where the DJF contribution reached 2.1% at Phu Quoc Station [103.97ºE, 10.22ºN].

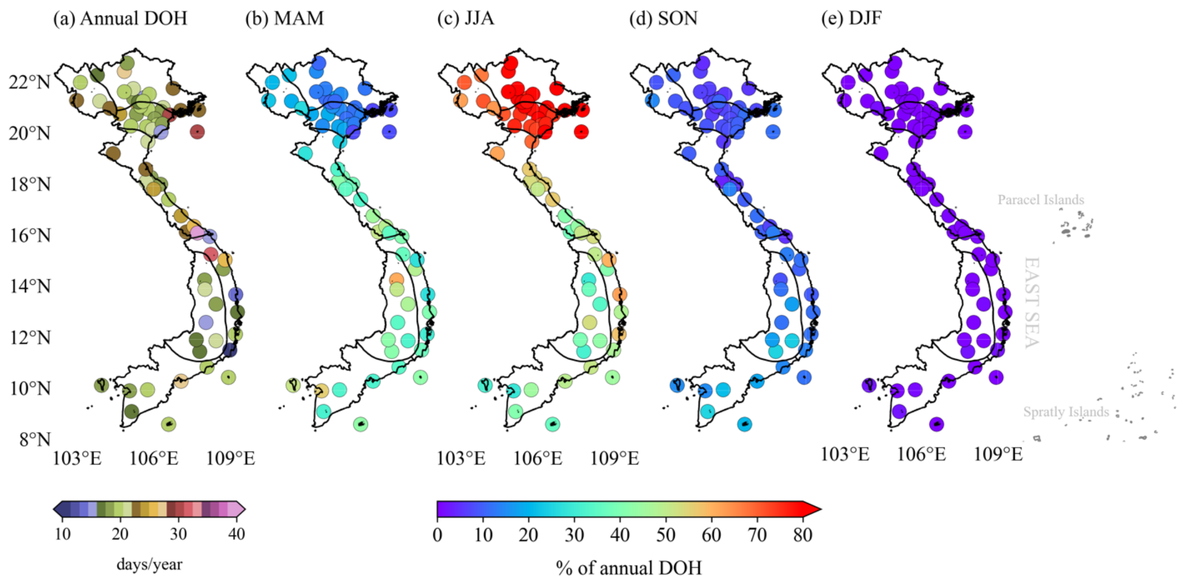

Figure 7. Spatial distributions of (a) the average annual number of DOH during 1979-2018 and (b-e) the contribution percentages by season.

Figure 8 displays the trends of annual and seasonal DOH for the 68 stations. We observe significant increases in annual DOH at most stations. NamDong Station [107.72ºE, 16.77ºN] in the North Central region has the highest DOH increase of 28.9 days/decade, followed by TraMy Station [108.25ºE, 15.333ºN] in the Central Highlands with 12.5 days/decade and BachLongVi Station [107.72ºE, 20.13ºN] in the North Delta with 11.4 days/decade. The stations in the North Central region have relatively higher DOH trends compared to those in other regions. DOH tends to decrease at some stations, such as PhuHo Station [105.23ºE, 21.45ºN] in the Northeast and BMThuot Station [108.05ºE, 12.67ºN] in the Central Highlands, which experience downward trends of -2.0 and -2.2 days/decade, respectively. However, these trends are not statistically significant. The DOH numbers during the MAM, JJA, and SON seasons also exhibit increasing trends at many stations. Since DOH is negligible in winter, most stations in Vietnam do not show pronounced DOH trends in DJF. Similar to the annual DOH, some stations exhibit downward trends in seasonal DOH, although these are not statistically significant at the 95% level. The number of DOH shows faster trends in JJA than in other seasons, suggesting enhanced severe heat stress during summer under climate change conditions.

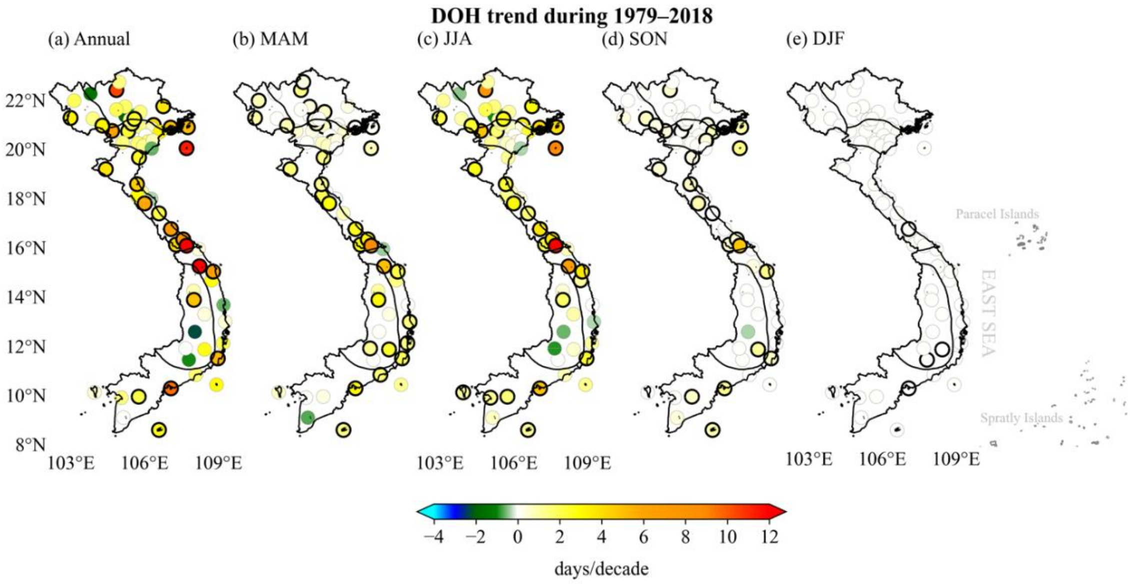

Figure 8. DOH trend during 1979-2018 for the annual average and the four seasons. The circles with black contours indicate where the trend is statistically significant at the 95% level.

4. DISCUSSION

According to the National Report on Climate Change and Sea Level Rise Scenario for Vietnam published in 2016 by the Ministry of Natural Resources and Environment (MONRE, 2016), Vietnam's temperature had increased by approximately 0.62ºC between 1958 and 2014. The report indicates that Tx had increased in most regions, except for some southern stations that experienced a decreasing trend. The updated 2020 scenario report (MONRE, 2020) revealed an increasing trend in the highest annual temperature (TXx) across most of the country, ranging from 0.2 to 1.7ºC during the period 1961-2018. However, in certain areas of the Northwest and Central Highlands, the annual average of Tx had decreased by 0.2 to 0.6ºC over 58 years (1961-2018).

It is worth noting that the reports mentioned above did not provide the statistical significance of the trends. Furthermore, comparing the increasing and decreasing trends between stations in the reports could lead to incoherent findings since the data period is not uniform for all the stations used in MONRE (2016) and MONRE (2020). Some stations, mainly in the North of Vietnam, have data collected since the 1960s, whereas many other stations in the Central and Southern regions have data only after 1975, when North and South Vietnam were unified after the war.

Our study has the advantage of using daily Tx and RH13 values that have been collected and processed uniformly between 1979 and 2018 across all stations. This uniformity enabled us to compare trends among stations and calculate average trends across each climatic sub-region and for the entire country. We also applied the Mann-Kendall test to determine the statistical significance of the trends. This analysis enabled us to identify significant increases in Tx at nearly all stations in Vietnam in autumn, in the North Delta in spring, and in the Central Highlands and the South in summer (Figure 2).

Concerning past humidity trends in Vietnam, Ngo-Duc and Phan-Van (2012) first explored the trend of daily minimum relative humidity during 1961-2007. However, their study was based on a limited number of monitoring stations, and they found no systematic change in the minimum humidity during the study period. In our analysis (Figure 3), we revisited their work using more up-to-date data from more stations to obtain a more comprehensive understanding of the distribution and trend of humidity in Vietnam.

Our study has revealed two significant features of RH13. Firstly, RH13 values in the Central Coast and Central Highlands regions are lower than in other regions during summer and winter/spring, respectively

(Figure 3). This can be explained by the foehn effect, which occurs when moist air rises over a mountain range and loses its moisture as it descends on the leeward side. This results in lower relative humidity in the Central Coast region during summer and in the Central Highlands during winter and spring (Nguyen-Le et al., 2014; Nguyen-Le et al., 2015). Secondly, the decreasing (increasing) trends of RH13 at various stations are possibly associated with the corresponding increasing (decreasing) trends of Tx, as depicted in Figures 2 and 4. This finding can be partly explained by the Clausius-Clapeyron relationship (Held and Soden, 2006), which states that in a warmer (cooler) climate, the atmosphere holds more (less) humidity, thereby resulting in a decrease (increase) in relative humidity.

It is worth noting that, to the best of our knowledge, this is the first time that the heat stress index has been calculated and analyzed using data sources from the network of meteorological stations in Vietnam. The heat stress thresholds determined in this study, which are based on the 95th percentile of TWmax values, are generally above 27ºC across most stations in Vietnam, in line with the findings of Kang and Eltahir (2018). These results provide useful benchmark values for future studies on heat stress in Vietnam.

In the context of global warming, the number of heat stress days has increased significantly in most parts of Vietnam over the past four decades. The typical increase, i.e. the interquartile range of values across all stations, ranges from 0.8 to 4.2 days per decade, and possibly even up to 28.9 days per decade. The results of this study indicate that there is an increasing risk of heat stress on health and productivity in Vietnam, particularly for outdoor workers (Parsons et al., 2022) during the summer months.

5. CONCLUSION

In this study, we examined the relationship between the daily maximum temperature Tx, the relative humidity RH13, and the heat stress index TWmax in Vietnam, with a focus on the spatial distribution and trends of these variables from 1979 to 2018. Our results revealed a close relationship between Tx and TWmax, whereas the impact of RH13 on TWmax was weak. We also observed a general increasing trend in Tx and TWmax across most stations, with RH13 showing both negative and positive trends. The heat stress thresholds used in this study resulted in a range of 10.5-36.1 heat stress days per year for the study period, with most stations experiencing more than 18.5 heat stress days per year. We also identified a significant increase in heat stress days over the past four decades across most of Vietnam, particularly in summer, which contributes the most to the annual number of heat stress days in most sub-regions.

Our study has established useful benchmark values for future research on heat stress in Vietnam and has provided a comprehensive understanding of the spatial distribution and trends of heat stress over the past four decades. In future work, we plan to project heat stress under different greenhouse gas scenarios in the 21st century using multiple downscaling experiments. As heat stress can have critical impacts on society, our findings are expected to provide insights for policymakers and researchers concerned with this issue in Vietnam.

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