

SPATIOTEMPORAL CHARACTERISTICS AND TRENDS OF HEAT EXTREMES IN LAO CAI PROVINCE, VIETNAM

Dao Ngoc Hung¹, Tran Bich Diep^{1,*}, Ly Thuy Nga¹, Bui Thi Hong Tuyet¹
and Cu Thi Phuong²

¹*Faculty of Geography, Hanoi National University of Education, Hanoi, Vietnam*

²*Vietnam Institute of Meteorology, Hydrology and Climate Change, Hanoi, Vietnam*

*Corresponding author: Tran Bich Diep, e-mail: trandiep100424@gmail.com

Received: January 23, 2026. Revised: March 3, 2026. Accepted: March 30, 2026.

Abstract. Heat extremes are among the most significant manifestations of climate change, posing increasing risks to human health, agriculture, and socio-economic activities. This study analyzes the characteristics and long-term trends of heat extremes in the Lao Cai region, northern Vietnam, over the period 1975 - 2024 using daily maximum temperature data from meteorological observation stations. The occurrences of hot days and heat waves were identified based on threshold-based indices and consecutive-day criteria. The results reveal a clear intensification of heat extremes, with significant increases in the frequency, intensity, and duration of hot days and heat waves, particularly in low-elevation areas. In contrast, stations located at elevations above 900 m experience minimum hot days, indicating a strong influence of topography on the spatial distribution of thermal extremes. Heat extremes exhibit strong seasonality, occurring mainly during the warm season from May to September. These findings demonstrate that mountainous regions such as Lao Cai are increasingly affected by extreme heat and provide a crucial scientific basis for heat risk assessment and climate adaptation planning.

Keywords: heat extremes; hot days; heat waves; daily maximum temperature; climate trends; Lao Cai province.

1. Introduction

Heat extremes, a prominent type of extreme weather event, have emerged as one of the most critical climate-related hazards under ongoing global warming. Numerous studies have documented significant increases in the frequency, intensity, and duration of extreme temperature events worldwide, leading to severe impacts on human health, ecosystems, agriculture, and socio-economic systems [1]-[3]. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), extreme

heat events have become more frequent and intense across most land regions since the mid-20th century, and this trend is projected to persist in the future [4].

Extreme heat is of particular concern because its intensity often increases more rapidly than mean temperature, resulting in a disproportionate rise in high-impact events [5]. Observational and modeling studies have shown that heat waves, commonly defined as prolonged periods of abnormally high temperatures lasting at least two consecutive days, relative to local climatic conditions, are becoming more frequent and persistent, thereby amplifying cumulative heat stress and associated risks [6], [7]. These findings highlight the necessity of detailed regional assessments of heat extremes based on long-term observational data. In Southeast Asia, heat extremes have intensified markedly in recent decades. Several studies have reported upward trends in the frequency of hot days and heat wave events across the region, driven by both global warming and regional climate variability. Vietnam has experienced a notable rise in extreme temperatures since the late 20th century, particularly in the northern regions, imposing significant impacts on agriculture, energy demand, and public health [8]. Most existing studies in Vietnam have focused on lowland, coastal, and urban areas, where heat-related impacts are often most acute. In contrast, mountainous regions have received relatively limited attention. Traditionally considered less vulnerable due to their cooler climates, mountainous areas are increasingly recognized as being highly sensitive to climate change. Recent research has highlighted the phenomenon of elevation-dependent warming (EDW), whereby temperature increases in mountainous regions may be comparable to or even exceed those in surrounding lowlands [9], [10].

Located in northern Vietnam, Lao Cai Province - re-established on July 1, 2025, according to Resolution No. 202/2025/QH15 dated June 12, 2025, by the 15th National Assembly of Vietnam - is characterized by complex terrain and large elevation gradients. Despite its mountainous setting, recent observations indicate that Lao Cai has experienced increasingly frequent and intense heat events in Vietnam. This study categorizes heat intensity into hot days ($35\text{ }^{\circ}\text{C} \leq T_{\text{max}} < 37\text{ }^{\circ}\text{C}$), severe hot days ($37\text{ }^{\circ}\text{C} \leq T_{\text{max}} < 39\text{ }^{\circ}\text{C}$), and extreme hot days ($T_{\text{max}} \geq 39\text{ }^{\circ}\text{C}$). However, comprehensive assessments of heat-extreme characteristics and long-term trends based on daily maximum temperature observations remain scarce for this region.

Therefore, the objectives of this study are to: (i) characterize the frequency and seasonal distribution of heat extremes in the Lao Cai region; (ii) analyze long-term trends in hot days, severe hot days, and extreme hot days over the period 1975 - 2024; and (iii) examine changes in the frequency and duration of heat wave events. By focusing on a mountainous region with complex topography, this study provides novel observational evidence of heat extreme intensification in northern Vietnam and contributes to a better understanding of heat-related climate hazards under global climate change.

2. Content

2.1. Study Area

Located in Northern Vietnam, Lao Cai Province is characterized by complex mountainous terrain with significant elevation gradients. Altitude ranges from low-lying

valleys below 200 meters to high-altitude mountain areas exceeding 3,000 meters above sea level, including the Hoang Lien Son range and Fansipan peak (3,143 meters) -the highest peak in both Vietnam and Indochina. This pronounced topographic variability exerts a strong influence on local climatic conditions and contributes to substantial spatial heterogeneity in temperature extremes.

The climate of Lao Cai is dominated by the tropical monsoon system, with a distinct warm season from May to September and a cooler season from October to April. Despite its mountainous setting, hot and humid conditions frequently occur during the warm season, particularly in low-elevation valleys where heat accumulation is enhanced by topographic confinement. During intense heat episodes, daily maximum temperatures in these areas may exceed 40°C, while high-elevation regions remain considerably cooler. This sharp thermal gradient within a limited geographic area makes Lao Cai a compelling case for investigating heat extremes in mountainous environments.

This study uses daily maximum temperature (Tmax) observations from meteorological stations located in Lao Cai Province and surrounding areas for the period 1975 - 2024. The data were obtained from the National Meteorological and Hydrological Network and subjected to standard quality control (QC) procedures, including checks for outliers, missing values, and temporal consistency. Only stations with sufficiently long and homogeneous records were included to ensure the statistical robustness of long-term trend analyses. For regional-scale analysis, heat extreme indices are averaged across stations to obtain representative regional mean values for Lao Cai Province. This approach is necessary because Lao Cai is a mountainous province with complex topography, characterized by distinct climatic conditions between high-altitude areas (Sa Pa – 1584 m, Bac Ha – 928 m, Mu Cang Chai – 955 m) and low-lying intermontane areas (Luc Yen – 105 m, Van Chan – 274 m, Pho Rang – 98 m, Yen Bai – 55 m). These elevation differences lead to significant spatial variability in temperature and heat extremes, making regional averaging essential for capturing representative characteristics.

2.2. Data sources

This study uses daily maximum air temperature data from meteorological stations in Lao Cai Province, Vietnam. The dataset was obtained from the National Meteorological and Hydrological Network and covers a sufficiently long period to analyze the characteristics of extreme temperatures and hot days.

The meteorological stations are distributed across various elevation zones, representing the diverse topographic and climatic conditions of the study area. This spatial coverage enables an assessment of spatial variations in maximum temperature associated with the complex terrain.

Daily maximum temperature (Tmax) was selected as the primary variable for identifying hot days, as it is directly related to daytime heat stress and is widely used in studies of temperature extremes and heat waves [6], [8]. Basic quality control (QC) procedures were applied to the dataset to remove missing and erroneous values, including checks for data completeness and temporal consistency [5]. Only stations with

continuous and homogeneous records were used in the analysis to ensure the reliability and consistency of the data.

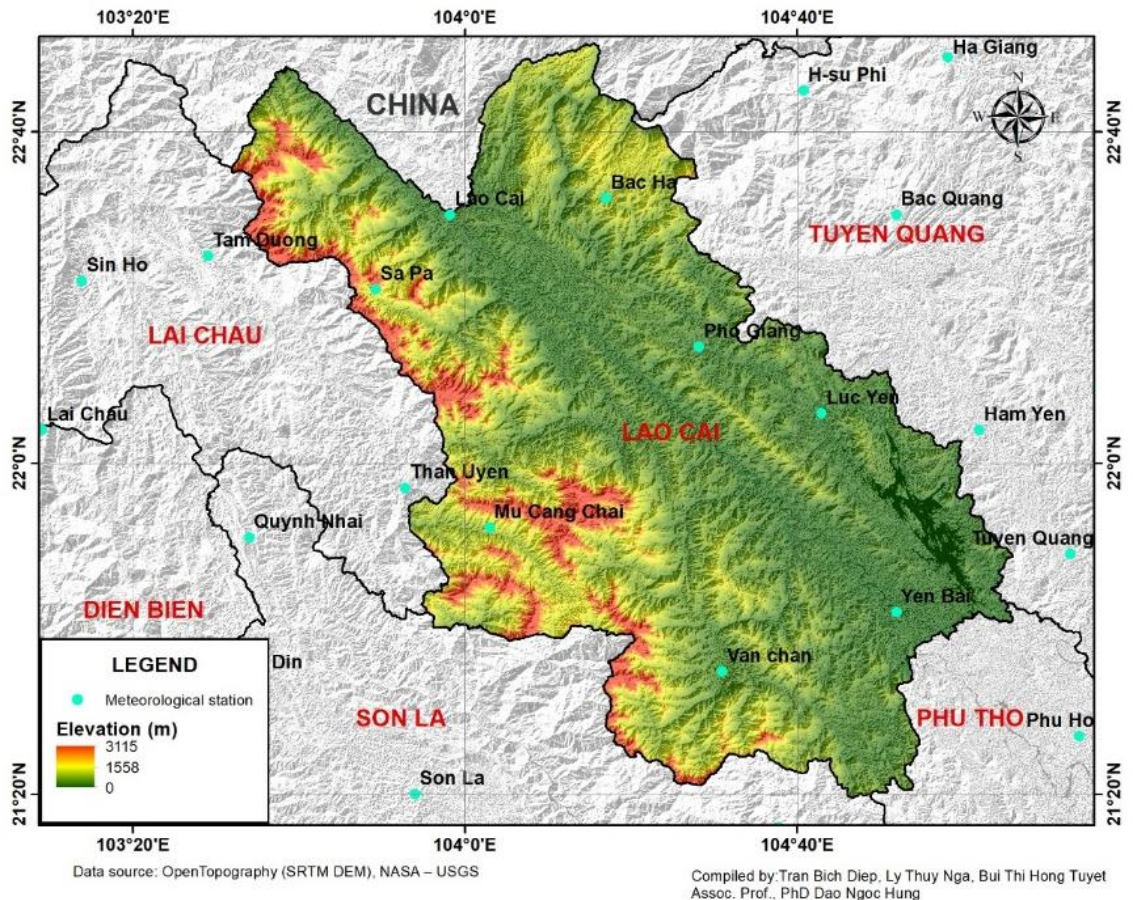


Figure 1. Study area and meteorological station network in Lao Cai Province, Vietnam

Daily maximum temperature is a fundamental variable for heat extreme assessment because it directly reflects daytime heat stress. The nearly 50-year dataset provides a reliable basis for examining seasonal characteristics, interannual variability, and long-term trends in both hot days and heat waves.

2.3. Methodology

2.3.1. Heat extreme indices

Heat extremes were defined using fixed temperature thresholds commonly applied in the meteorological service of northern Vietnam. Three categories of heat density were considered:

- Hot days: $35\text{ }^{\circ}\text{C} \leq T_{\text{max}} < 37\text{ }^{\circ}\text{C}$
- Severe hot days: $37\text{ }^{\circ}\text{C} \leq T_{\text{max}} < 39\text{ }^{\circ}\text{C}$
- Extreme hot days: $T_{\text{max}} \geq 39\text{ }^{\circ}\text{C}$

For each station, the annual number of days within each category was calculated. Group-level values were derived by averaging station-level indices within each

elevation category. In addition to threshold-based indices, the annual mean daily maximum temperature (Tmax_mean) was computed to represent the background warming conditions.

2.3.2 Trend analysis and statistical methods

Temporal trends in Tmax_mean and heat extreme indices were evaluated using both parametric and non-parametric approaches.

Linear regression was applied to estimate the rate of change over time [11], [12]:

$$X(t) = a \cdot t + b$$

where $X(t)$ represents the annual value of the index for the year t , a is the trend slope (rate of change), and b is the intercept.

The statistical significance of monotonic trends was assessed using the non-parametric Mann-Kendall (MK) test [12], [13], which is robust against non-normal distributions and outliers. The MK test statistic S is defined as

$$S = \sum_{\{i=1\}^{\{n-1\}}} \sum_{\{j=i+1\}^{\{n\}}} \text{sgn}(x_j - x_i), \quad j > i$$

For sample sizes greater than 10, the standardized test statistic Z was calculated to determine significance levels. Trends were considered statistically significant at the 95% confidence level ($p < 0.05$).

The magnitude of monotonic trends was further quantified using Sen's slope estimator [12], [14]:

$$Q = \text{median}\left(\frac{x_j - x_i}{j - i}\right), \quad j > i$$

Trend slopes are expressed in °C per decade for Tmax_mean and days per decade for heat extreme indices.

Due to the limited number of stations and strong topographic control, analyses were conducted at the station and elevation-group levels rather than through spatial interpolation.

2.4. Results and discussion

2.4.1. Long-term changes in annual mean daily Tmax (1975–2024)

The annual mean daily maximum temperature (Tmax_mean) during 1975 - 2024 shows a persistent and statistically significant warming tendency across nearly all stations (Figure 2). Although interannual variability is evident throughout the record, particularly during the late 1980s and early 1990s, the long-term evolution is characterized by a clear upward trajectory.

Low-elevation stations (< 300 m) exhibit more pronounced warming compared to high-elevation sites (> 900 m). The warming signal becomes especially pronounced after the mid-1990s and has intensified further after 2010, suggesting an acceleration of background warming over recent decades. This pattern is consistent with broader regional warming trends observed in northern Vietnam and Southeast Asia.

The mean annual T_{max_mean} difference between low- and high-elevation groups remains approximately 5 °C throughout the study period (Figure 3), indicating a stable and persistent elevation-dependent thermal gradient. While both groups show warming trends over time, the magnitude of warming is systematically greater at lower elevations. This suggests that valley and lowland environments not only maintain higher baseline temperatures but also respond more sensitively to regional climate warming.

The stronger warming at low elevations may be associated with several mechanisms, including enhanced heat accumulation in topographically confined valleys, reduced ventilation under weak synoptic-scale conditions, and potential land-use or urbanization influences in lowland districts. In contrast, high-elevation stations such as Sa Pa remain thermally moderated by altitude and higher ventilation rates, which may dampen the amplification of extreme temperature amplification.

Importantly, the upward shift in T_{max_mean} provides the thermodynamic baseline for increases in threshold-defined heat extremes. Even modest increases in mean temperature can produce disproportionately large increases in the frequency of high-temperature exceedances due to the non-linear nature of temperature distributions.

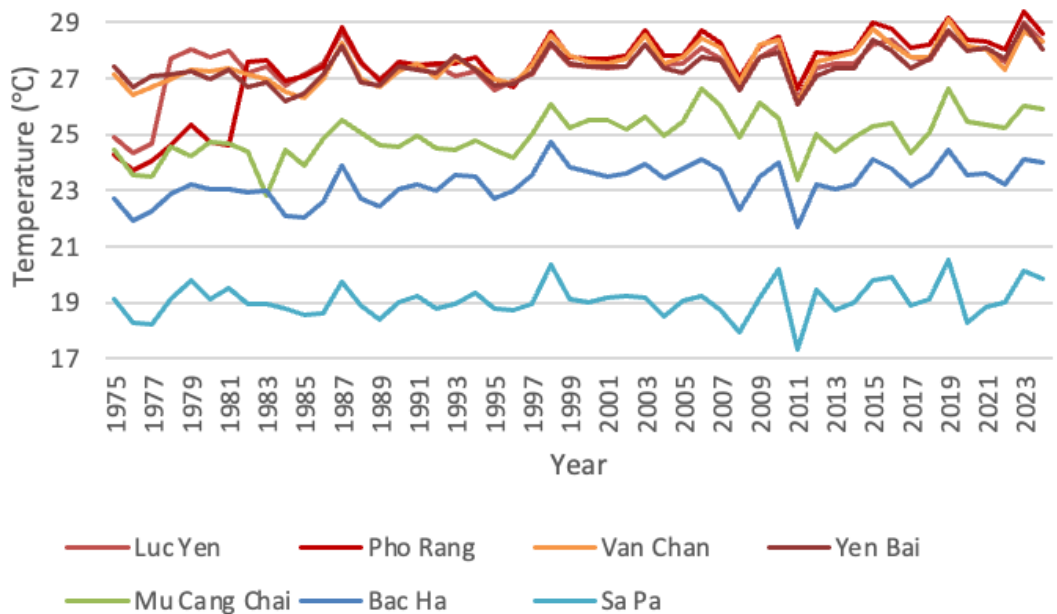


Figure 2. Annual mean daily maximum temperature (T_{max_mean}) at seven meteorological stations in the Lao Cai region during 1975 – 2024

The annual frequency of hot days $35\text{ °C} \leq T_{max} < 37\text{ °C}$ shows a marked increase at low-elevation stations (Figure 4). The most substantial growth is observed at Pho Rang, where the number of hot days has increased steadily throughout the record, with a particularly rapid escalation after 2000. Similar but slightly weaker upward tendencies are observed at Luc Yen, Yen Bai, and Van Chan.

The interannual variability of hot-day frequency is notable, reflecting the influence of large-scale atmospheric circulation patterns and monsoonal variability. Years characterized by anomalously high hot-day counts often correspond to periods of strong atmospheric subsidence, reduced cloud cover, or regional drought conditions. Nevertheless, despite these fluctuations, the long-term trend remains clearly positive at all low-elevation stations.

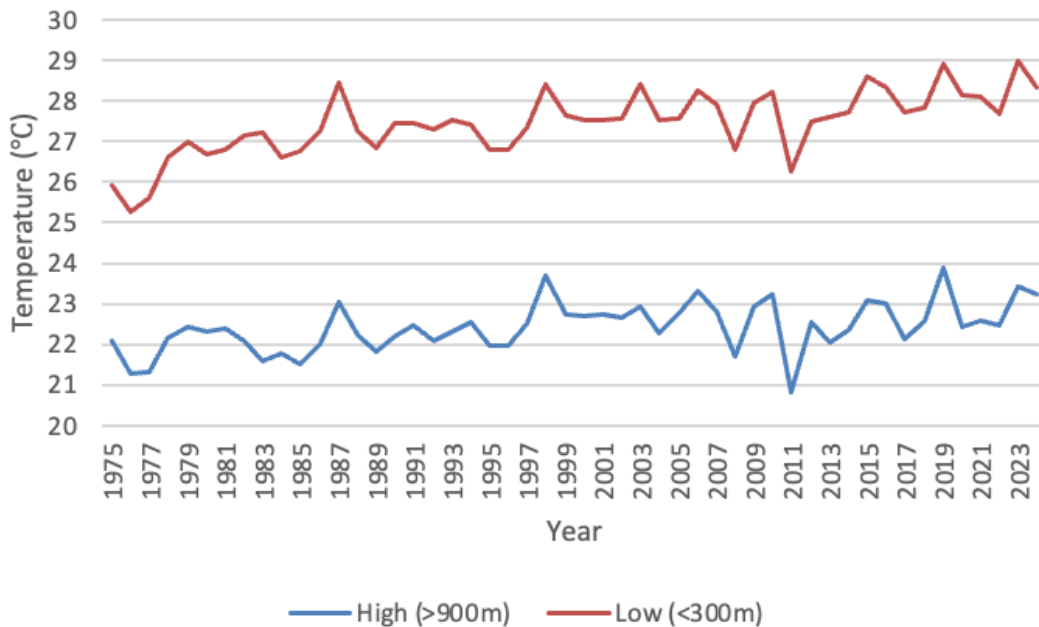


Figure 3. Annual mean daily maximum temperature (T_{max_mean}) averaged for high-elevation (> 900 m) and low-elevation (< 300 m) stations during 1975 - 2024

2.4.2. Trends in hot days ($35\text{ }^{\circ}\text{C} \leq T_{max} < 37\text{ }^{\circ}\text{C}$)

In contrast, high-elevation stations record very few occurrences of $T_{max} \geq 35\text{ }^{\circ}\text{C}$ during the entire 50-year period. The frequency remains near zero in most years, with only isolated exceedances at Bac Ha and Mu Cang Chai. Sa Pa, located at a higher elevation, consistently does not reach the $35\text{ }^{\circ}\text{C}$ threshold. This sharp difference underscores the dominant control of elevation on threshold-based heat metrics.

The divergence between elevation groups has become more pronounced in recent decades, as low-elevation stations experience accelerated increases in hot-day frequency, while high-elevation stations remain largely unaffected in terms of threshold exceedance. This suggests that background warming is pushing lowland temperatures more frequently beyond critical heat thresholds, whereas high-altitude environments predominantly remain below those limits.

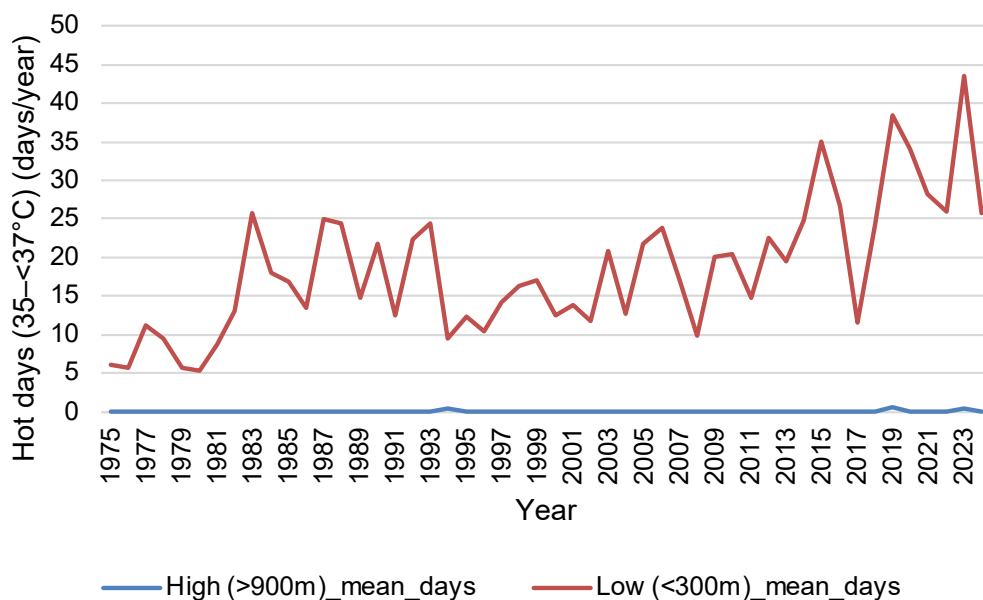


Figure 4. Annual number of hot days ($35\text{ }^{\circ}\text{C} \leq T_{\text{max}} < 37\text{ }^{\circ}\text{C}$) averaged for high-elevation ($> 900\text{ m}$) and low-elevation ($< 300\text{ m}$) stations during 1975 - 2024

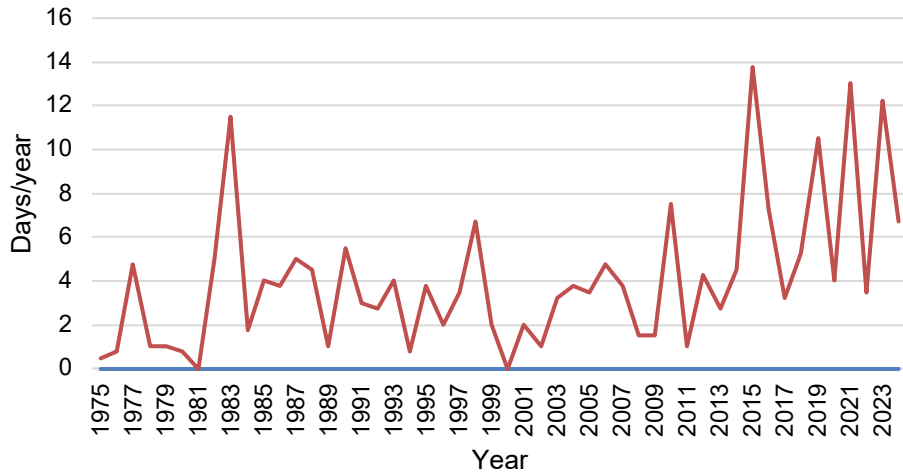
2.4.3. Severe and extreme hot days ($T_{\text{max}} \geq 37\text{ }^{\circ}\text{C}$)

Severe hot days $T_{\text{max}} \geq 37\text{ }^{\circ}\text{C}$ display spatial and temporal patterns similar to moderate hot days but with greater sensitivity to background warming (Figure 5). Low-elevation stations show clear increasing trends, with Pho Rang exhibiting the strongest rise, followed by Yen Bai, Van Chan, and Luc Yen. The increase has become particularly evident after the late 1990s, coinciding with the period of accelerated regional warming.

Extreme hot days ($\geq 39\text{ }^{\circ}\text{C}$), although much less frequent than moderate hot days, have demonstrated a noticeable emergence in recent decades. The occurrence of $T_{\text{max}} \geq 39\text{ }^{\circ}\text{C}$ events has increased significantly at several low-elevation stations, especially Pho Rang and Van Chan. The upward tendency of these high-intensity events suggests not merely a shift in mean conditions but an amplification of the upper tail of the temperature distribution.

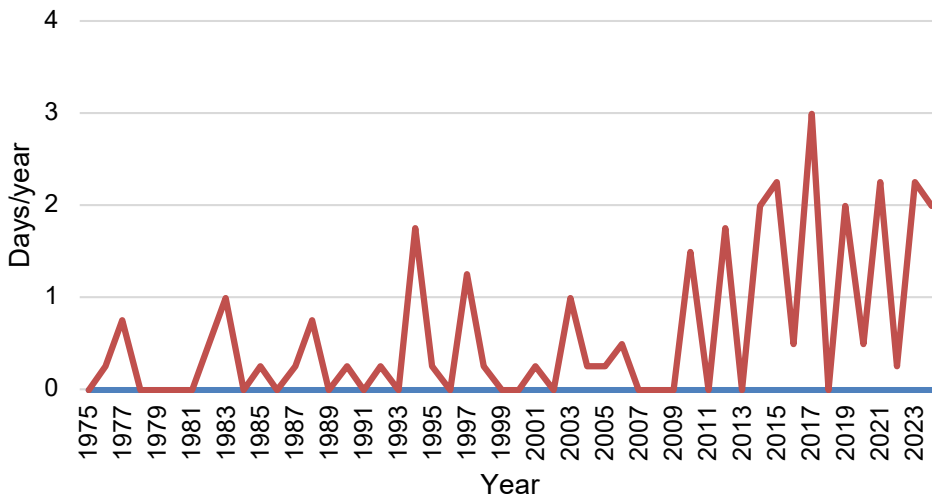
The disproportionate increase in higher temperature categories relative to moderate hot days reflects the non-linear response of extreme temperatures to climate warming. As $T_{\text{max_mean}}$ increases, the probability distribution shifts, resulting in more frequent exceedances of higher thresholds. This phenomenon has been widely documented in global and regional studies of temperature extremes.

High-elevation stations show virtually no severe or extreme hot days during the entire study period. Even under ongoing warming, T_{max} values at these sites rarely approach the $37\text{ }^{\circ}\text{C}$ threshold. This reinforces the strong topographic modulation of extreme heat occurrence and indicates that elevation acts as a buffering factor against threshold-defined thermal extremes.



— High (>900m)_mean_days — Low (<300m)_mean_days

(a)



— High (>900m)_mean_days — Low (<300m)_mean_days

(b)

Figure 5. (a) Severe hot days ($37\text{ }^{\circ}\text{C} \leq T_{max} < 39\text{ }^{\circ}\text{C}$) and (b) extreme hot days ($T_{max} \geq 39\text{ }^{\circ}\text{C}$) for high- and low-elevation station groups during 1975–2024

2.4.4. Elevation-based contrast and regional implications

The combined evidence from Figures 2-5 reveals a clear and persistent two-zone thermal regime in the Lao Cai–Yen Bai mountainous region. While both elevation groups experience significant background warming, the manifestation of threshold-defined heat extremes is predominantly concentrated in low-elevation environments.

The approximately $5\text{ }^{\circ}\text{C}$ baseline difference in T_{max_mean} between elevation groups acts as a fundamental control on extreme heat occurrence. Even with comparable

warming rates, the higher initial temperature in low-elevation areas makes them substantially more vulnerable to frequent exceedance of critical heat thresholds.

This elevation-dependent asymmetry has important implications for regional heat-risk assessment. Valley and lowland districts face increasing exposure not only to more frequent hot days but also to more intense heat categories. Such conditions can intensify heat stress on agriculture, escalate water demand, heighten wildfire risk, and pose significant hazards to vulnerable populations.

In contrast, high-elevation communities remain relatively protected from threshold-defined hot extremes, although continued warming may gradually erode this margin of thermal safety in the long term. Monitoring of high-elevation stations remains essential to detect potential threshold-exceedance shifts under future warming scenarios.

Overall, the results demonstrate that elevation exerts a strong and persistent control on both mean temperature and extreme heat characteristics. The intensification of heat extremes at low elevations underscores the need for targeted climate-adaptation strategies focusing on valley and lowland areas, where exposure and vulnerability to extreme heat are increasing most rapidly.

2.4.5. Seasonal distribution of hot days

Figure 6 shows the monthly distribution of hot days averaged over the entire study period. Because hot days, severe hot days, and extreme hot days are virtually absent at stations located above 900 m, the seasonal distribution of hot days in the study area is analyzed primarily for low-elevation stations below 300 m. The results indicate a strong seasonal dependence, with hot days exclusively concentrated during the warm season from May to September.

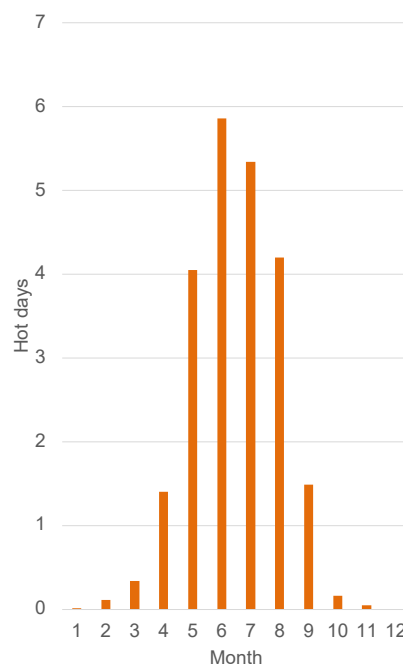


Figure 6. Monthly distribution of hot days ($T_{max} > 35\text{ }^{\circ}\text{C}$) averaged over the Lao Cai region during 1975 - 2024

Peak frequencies are observed in June and July, corresponding to periods of maximum solar radiation and favorable large-scale atmospheric conditions for heat accumulation. In contrast, hot days are virtually absent during the winter months from December to February. This pronounced seasonal cycle is consistent with the monsoonal climate of northern Vietnam and is well-documented in previous studies [8].

The strong seasonality of heat extremes implies that heat-related risks in the Lao Cai region are highly concentrated within a specific period of the year. Similar seasonal characteristics of hot days have been documented across northern Vietnam and other monsoon-dominated regions [8]. This finding carries important implications for seasonal heatwave early warning systems and climate adaptation planning, particularly in mountainous communities where adaptive capacity to extreme heat may be limited [9], [10].

3. Conclusions

This study analyzed the characteristics and long-term trends of heat extremes in the Lao Cai region, northern Vietnam, during 1975 - 2024 based on daily maximum temperature observations. The results indicate a clear intensification of heat extremes in this mountainous region. Hot days, severe hot days, and extreme hot days are virtually absent in high-elevation areas above 900 m in Lao Cai. In contrast, low-lying regions (below 300 m) exhibit pronounced characteristics and significant upward trends of heat extremes, as follows:

The annual number of hot days ($T_{\max} \geq 35 \text{ }^{\circ}\text{C}$) increased significantly, by approximately 6 - 7 days per decade. Severe ($T_{\max} \geq 37 \text{ }^{\circ}\text{C}$) and extreme hot days ($T_{\max} \geq 39 \text{ }^{\circ}\text{C}$) also exhibited marked upward trends, indicating a significant shift toward more intense heat extremes. Heat extremes showed strong seasonality, occurring almost exclusively during the warm season from May to September, with peak frequencies in June and July.

In addition, heat wave events have become more frequent and more persistent over time. The frequency of heat waves increased by about 2 events per decade, while the maximum duration increased by nearly 3 days per decade, highlighting growing risks associated with prolonged extreme heat.

Overall, the findings demonstrate that mountainous regions such as Lao Cai are not immune to extreme heat and are experiencing pronounced increases in heat extreme frequency, intensity, and persistence. These results provide robust scientific evidence for heat risk assessment and climate adaptation planning in mountainous areas of northern Vietnam.

REFERENCES

- [1] Perkins SE, Alexander LV & Nairn JR, (2012). Increasing frequency, intensity, and duration of observed global heatwaves and warm spells. *Geophysical Research Letters*, 39, L20714. <https://doi.org/10.1029/2012GL053361>.
- [2] Seneviratne SI, Donat MG, Mueller B & Alexander LV, (2014). No pause in the increase of hot temperature extremes. *Nature Climate Change*, 4, 161-163. <https://doi.org/10.1038/nclimate2145>.

- [3] Donat MG, Alexander LV, Yang H, et al., (2013). Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century. *Journal of Geophysical Research: Atmospheres*, 118, 2098-2118. <https://doi.org/10.1002/jgrd.50150>.
- [4] IPCC, (2021). *Climate Change 2021: The Physical Science Basis*. Cambridge University Press. <https://doi.org/10.1017/9781009157896>.
- [5] Seneviratne SI, Rogelj J, Séférian R, et al., (2016). Challenges in quantifying changes in climate extremes. *Nature Climate Change*, 6, 343-351. <https://doi.org/10.1038/nclimate2905>.
- [6] Fischer EM & Schär C, (2010). Consistent geographical patterns of changes in high-impact European heatwaves. *Nature Geoscience*, 3, 398-403. <https://doi.org/10.1038/ngeo866>.
- [7] Meehl GA & Tebaldi C, (2004). More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, 305, 994-997. <https://doi.org/10.1126/science.1098704>.
- [8] Nguyen TH, Phan VT & Nguyen QH, (2018). Changes in temperature extremes over Vietnam. *International Journal of Climatology*, 38, 1-15. <https://doi.org/10.1002/joc.5210>.
- [9] Pepin NC, Bradley RS, Diaz HF & et al., (2015). Elevation-dependent warming in mountain regions of the world. *Nature Climate Change*, 5, 424-430. <https://doi.org/10.1038/nclimate2563>.
- [10] Palazzi E, Mortarini L, Terzago S & von Hardenberg J, (2019). Elevation-dependent warming in global climate model simulations at high spatial resolution. *Climate Dynamics*, 52, 2685–2702. <https://doi.org/10.1007/s00382-018-4287-z>.
- [11] Perkins-Kirkpatrick SE & Gibson PB, (2017). Changes in regional heatwave characteristics as a function of increasing global temperature. *Scientific Reports*, 7, 12256. <https://doi.org/10.1038/s41598-017-12520-2>.
- [12] Zhang X, Zwiers FW & Li G, (2004). Monte Carlo experiments on the detection of trends in extreme values. *Journal of Climate*, 17, 1945-1952. https://journals.ametsoc.org/view/journals/clim/17/10/1520-0442_2004_017_1945_mceotd_2.0.co_2.xml.
- [13] Rahmstorf S & Coumou D, (2011). Increase of extreme events in a warming world. *Proceedings of the National Academy of Sciences*, 108, 17905-17909. <https://doi.org/10.1073/pnas.1101766108>.
- [14] Hegerl GC, Zwiers FW, Braconnot P & et al., (2007). *Understanding and attributing climate change*. In “IPCC Fourth Assessment Report”. Cambridge University Press.