



Regional patterns of heatwave intensification in Vietnam under global warming levels based on CMIP6 projections

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The present study examines heatwave intensification across Vietnam under global warming levels (GWLs) of 1.5–4°C using high-resolution CMIP6-VN data from 20 downscaled models. Applying the excess heat factor methodology, we analyse four heatwave characteristics – intensity (HWI), duration (HWD), frequency (HWF), and peak temperature (HWP) – across seven sub-climate regions, validated against observations from 146 meteorological stations (1995–2014). Results reveal severe escalation with rising GWLs: HWI increases from 2.80°C² to 4.25°C², HWD from 13.6 to 118 days annually, HWF from 3.7 to 12.4 events, and HWP by 1.04°C nationally. Northern regions show greater intensity and frequency increases, while southern areas, especially R7, experience durations exceeding 160 days, highlighting stark regional disparities. Non-linear escalation beyond 3°C emerges with stronger model agreement (SNR > 1) at higher GWLs. These findings illustrate Vietnam's acute vulnerability to heatwave extremes threatening agriculture, health, and infrastructure, emphasising urgent needs for region-specific adaptation strategies. With global temperatures reaching 1.55°C above pre-industrial levels in 2024, this research provides critical evidence for policymakers to strengthen climate resilience and support international efforts to limit warming.

Keywords. Heatwave; Vietnam; global warming levels; CMIP6-VN; climate change adaptation.

1. Introduction

Global warming, driven primarily by anthropogenic greenhouse gas emissions, has become as one of the most pressing challenges of the 21st century, with the global mean surface temperature

(GMST) rising by approximately 1.09°C above pre-industrial levels during 2011–2020 (IPCC 2021). This warming has amplified the frequency, intensity, and duration of extreme weather events, with heatwaves standing out as particularly devastating due to their widespread impacts on human

health, infrastructure, agriculture, and ecosystems (Trenberth 2018; AghaKouchak *et al.* 2020; Jha and Dev 2024). Heatwaves, defined as prolonged periods of very high temperatures, are known as the severe natural hazards globally, contributing to increased mortality, crop failures, wildfires, and infrastructure strain (Meehl and Tebaldi 2004; Smith *et al.* 2013). The Intergovernmental Panel on Climate Change (IPCC) projects that under high-emission scenarios, such as SSP5-8.5, global temperatures could rise by up to 4.4°C by 2100, potentially leading to near-constant heatwave conditions in tropical regions (IPCC 2021).

Vietnam, a country highly vulnerable to climate change, faces significant risks from intensifying heatwaves due to its geographical, socio-economic, and environmental characteristics (Eckstein *et al.* 2021; Woillez 2024). The country has already experienced a notable increase in average and extreme temperatures over recent decades, with heatwaves becoming more frequent and severe, particularly in northern and central regions (Woillez 2024; Nguyen-Le *et al.* 2025). These changes threaten Vietnam's economy, where over 60% of the workforce is employed in weather-dependent sectors such as agriculture and fisheries (GSO Vietnam 2021). For instance, temperatures exceeding 35°C during the rice flowering stage can reduce yields by up to 10%, while a 2°C global temperature rise could halve the suitable area for Pangasius farming in the Mekong Delta (FAO 2022; Tho and Umetsu 2022). Additionally, heatwaves exacerbate health risks, particularly for vulnerable populations such as the elderly, children, and those with pre-existing conditions, while urban heat island effects amplify heat stress in densely populated areas.

Despite the growing global literature on heatwaves, significant gaps remain in understanding their regional dynamics, particularly in vulnerable regions like Vietnam. Previous studies have primarily focused on global or mid-latitude trends, analysing heatwave metrics such as frequency, duration, intensity, and spatial extent (Al-Yaari *et al.* 2023; Hu *et al.* 2023; Zeder and Fischer 2023). However, these studies often rely on coarse-resolution datasets that fail to capture fine-scale spatial variations critical for regional analysis. Moreover, while metrics like the excess heat factor (EHF) have been widely adopted to assess heatwave impacts on human health by accounting for temperature thresholds and population adaptation (Nairn and Fawcett 2014; Jangi *et al.* 2024), their

application in tropical regions like Vietnam remains limited. The EHF, endorsed by the World Health Organisation (WHO) and World Meteorological Organisation (WMO), is particularly valuable for its ability to quantify HWI in both tropical and temperate climates (WMO 2023). Additionally, there is a lack of comprehensive studies comparing observed and projected heatwave trends under various global warming scenarios, particularly at regional scales, which hinders the development of targeted adaptation strategies.

To address these gaps, this study leverages the high-resolution CMIP6-VN dataset, derived from statistically downscaled Coupled Model Intercomparison Project Phase 6 (CMIP6) models, to investigate heatwave trends in Vietnam under global warming levels (GWLs) ranging from 1.5°C to 4°C (Espagne *et al.* 2021; Tran-Anh *et al.* 2023). Unlike previous national assessments by the Ministry of Natural Resources and Environment (MONRE), which relied on limited model experiments and dynamic downscaling (MONRE 2009; MONRE 2012; MONRE 2016; MONRE 2021), the CMIP6-VN dataset offers a 10 km resolution and incorporates a broader range of emission scenarios, enabling a more detailed analysis of regional climate patterns. We focus on four key heatwave metrics – intensity, duration, frequency, and peak temperature – using the EHF and percentile-based definitions to assess spatiotemporal variations across Vietnam during a baseline period (1986–2005) and future periods (2026–2099). This study addresses two primary questions: (i) Will heatwave characteristics intensify more rapidly in the future under different GWLs? (ii) How will these characteristics vary spatially across Vietnam, and where are the likely hotspots for extreme heat events? By quantifying these trends and identifying regional vulnerabilities, this research aims to provide a robust foundation for policymakers to develop climate adaptation and mitigation strategies tailored to Vietnam's diverse regions.

This study aims to enhance understanding of heatwave dynamics in a nation especially exposed to climate shifts. By integrating high-resolution climate projections with advanced heatwave metrics, we aim to bridge the gap between global climate trends and local-scale impacts, offering actionable insights for sectors such as agriculture, public health, and urban planning. The findings are expected to guide Vietnam's climate resilience strategies, aligning with global commitments like the Paris Agreement, which emphasises limiting

warming to 1.5°C to mitigate severe climate risks (UNFCCC 2015). As heatwaves continue to pose increasing threats under a warming climate, this study underscores the urgency of proactive measures to protect Vietnam's population, economy, and ecosystems from the escalating impacts of extreme heat.

2. Materials and method

2.1 In-situ observation temperature data

This study analysed maximum daily temperature observations from 146 meteorological stations across Vietnam from 1995 to 2014 (figure 1). The stations provide comprehensive coverage of Vietnam's diverse climatic conditions across seven sub-climate regions. All calculations of heatwave indices were performed at the grid-cell level using gridded CMIP6-VN climate model outputs, and regional statistics were subsequently obtained by spatially averaging the grid-based results within

each climatic region. Following, Nguyen and Nguyen (2004) climate classification based on radiation, temperature, and precipitation criteria, Vietnam is divided into seven climatic subregions: Northwest (R1), Northeast (R2), Red River Delta (R3), North Central (R4), Central South (R5), Central Highlands (R6), and Southern (R7). The analysis focuses exclusively on continental Vietnam, excluding islands in the East Sea.

2.2 Global warming levels

GWs occur when the GMST, averaged over land and ocean, surpasses a specific threshold relative to the pre-industrial period (1850–1900). This study uses a 21-year window, centered on the year of exceedance (YEX) – the first year a CMIP6 model exceeds the GWL threshold – incorporating 10 years before and after YEX to minimise short-term variability. For instance, if a model's GMST exceeds the 2°C threshold in 2040, the 2°C GWL period spans 2030–2050, with 2040 as the midpoint.

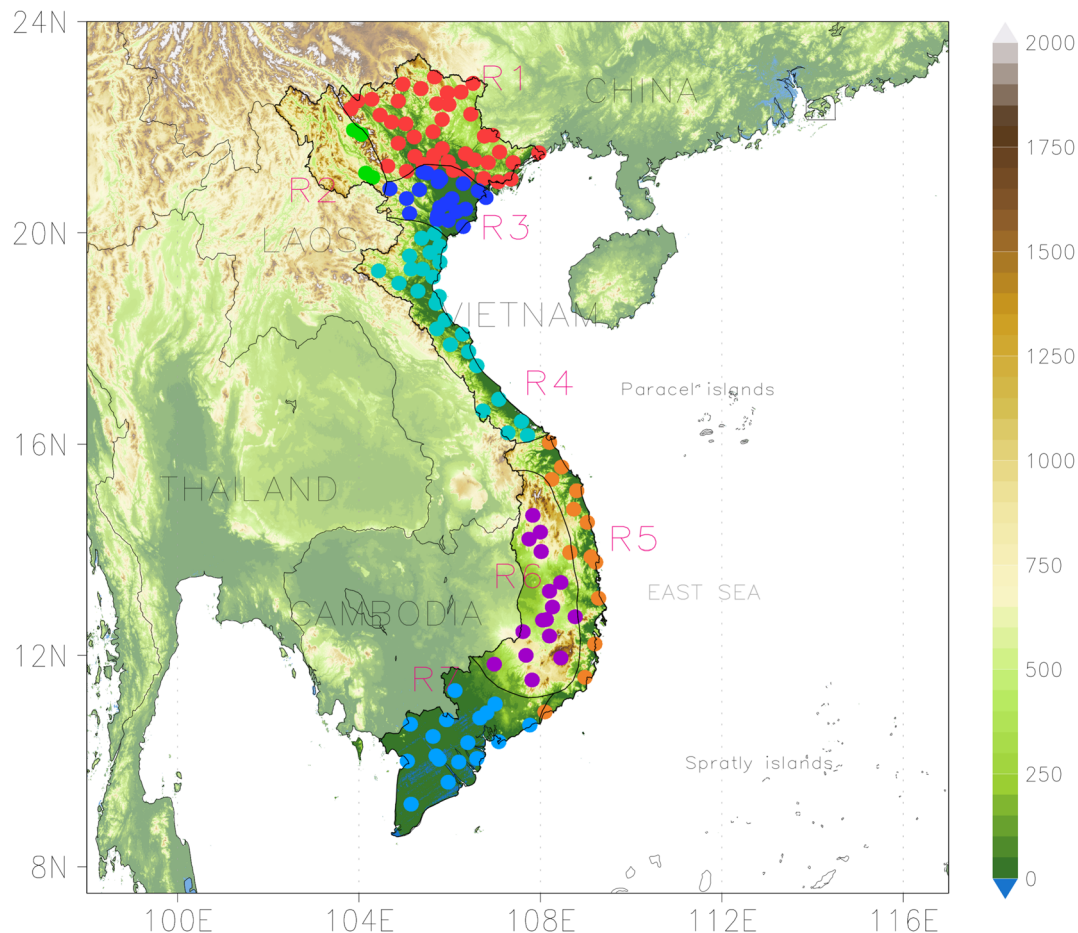


Figure 1. Locations of 146 temperature stations used in this study across seven sub-climate regions of Vietnam. Stations within the same region are shown in the same color. Topographic data are derived from HydroSHEDS (Linke *et al.* 2019).

The climate response for a GWL is calculated by averaging results across all models and SSP scenarios that reach that threshold. This approach is consistent with Hausfather *et al.* (2022), who applied a 20-year window (10 years before and 9 years after YEX), with both methods producing comparable climatological results due to the balanced period around YEX. The climatological values and the changes between the future and baseline periods are nearly identical for the 21-year and 20-year windows (not shown). For example, if the global temperature simulated by a given GCM first exceeds the 2°C threshold in 2040, the period of exceeding the 2°C GWL is defined between 2030 and 2050, with 2040 as the central year. Then, the climate response pattern for a given GWL is calculated as the average across all models and scenarios that reach that GWL.

2.3 CMIP6-VN dataset

The IPCC's Sixth Assessment Report (IPCC 2021) outlines a framework for projecting future climate scenarios through the CMIP6. Introduced in 2015, CMIP6 includes a core set of scenarios that model potential climate futures based on different socioeconomic pathways and their associated greenhouse gas emissions, aerosols, ozone-depleting substances, and land-use changes. The CMIP6 scenarios, referred to as shared socioeconomic pathway-representative concentration pathway (SSP-RCP) combinations, are named using the format SSPx-y. Here, 'SSPx' describes a specific socioeconomic storyline – such as population growth, economic development, or global cooperation (Riahi *et al.* 2017) – while 'y' represents the level of radiative forcing (measured in watts per square metre, W/m²) expected by the year 2100, which indicates the intensity of climate change due to greenhouse gas emissions. The five scenarios considered in this study are:

- SSP1-1.9: A sustainable future with strong climate action, keeping warming to 1.5°C.
- SSP1-2.6: A green pathway with effective policies, limiting warming to below 2°C.
- SSP2-4.5: A balanced scenario with moderate efforts, leading to about 2.7°C warming by 2100.
- SSP3-7.0: A divided world with weak climate policies, resulting in roughly 3.6°C warming.
- SSP5-8.5: A high-emission future reliant on fossil fuels, causing around 4.4°C warming by 2100.

To assess the impacts of these scenarios on Vietnam, this study utilises the CMIP6-VN dataset (Tran-Anh *et al.* 2023). This dataset provides high-resolution climate projections tailored for Vietnam, using the bias correction and spatial disaggregation (BCSD) method to down-scale CMIP6 model outputs to a 10 km grid for improved local accuracy. For consistency with GWL analyses, 20 CMIP6 models were selected based on their availability in both the CMIP6-VN dataset and the GWL threshold database (Hauser *et al.* 2019). The CMIP6-VN dataset can be downloaded from: <https://doi.org/10.6084/m9.figshare.c.6164352>. Table 1 lists the CMIP6-VN models and the corresponding scenarios analysed in this study.

2.4 Definition of heatwave

A heatwave is defined as a period of unusually high temperatures that pose significant risks to human health, infrastructure, and ecosystems, marked by sustained excess heat accumulation over multiple days (Perkins 2015; Panda *et al.* 2017). In this study, heatwaves are evaluated using the EHF – a metric designed to monitor and forecast HWI and severity with a focus on human health impacts (Nairn *et al.* 2009; Nairn and Fawcett 2011; Perkins and Alexander 2012). The EHF is derived from the daily mean temperature (DMT), denoted as T_i , which is the average of the daily maximum and minimum temperatures for day i , reflecting the physiological impact of a hot night following a hot day. This approach is motivated by epidemiological studies showing health effects, such as increased mortality, after 1–3 days of extreme heat in cities like Melbourne and Adelaide (Banwell *et al.* 2012).

The EHF is calculated using two excess heat indices over a three-day period (TDP). The first index, the significance index, is given by

$$\text{EHF}_{\text{sig}} = \frac{T_i + T_{i+1} + T_{i+2}}{3} - T_{95} \quad (1)$$

where T_{95} is the local 95th percentile of DMT based on climatological data from 1995–2014, assessing absolute heat relative to the annual climate. A positive EHF_{sig} indicates the TDP is unusually warm, a prerequisite for a heatwave, typically excluding winter half-year events.

Table 1. List of the 20 statistically downscaled CMIP6 GCMs (CMIP6-VN database, Tran-Anh *et al.* (2023)) and available scenarios selected for this study. The column ‘country’ indicates where the models are developed.

CMIP6 Model	Country	Horizontal resolution (lat. × long. in degree)	Historical	SSP1-	SSP1-	SSP2-	SSP3-	SSP5-
			period 1980–2014	1.9	2.6	4.5	7.0	8.5
						2015–2099		
ACCESS-ESM1-5	Australia	$1.88 \times 1.25^\circ$	x	–	x	x	x	x
AWI-CM-1-1-MR	Germany	$0.93 \times 0.94^\circ$	x	–	x	x	x	x
BCC-CSM2-MR	China	$1.13 \times 1.13^\circ$	x	–	x	x	x	x
CMCC-ESM2	Italia	$1.25 \times 1.25^\circ$	x	–	x	x	x	x
CNRM-CM6-1-HR	France	$1.25 \times 0.94^\circ$	x	–	x	x	x	x
CNRM-ESM2-1	France	$0.5 \times 0.5^\circ$	x	x	x	x	x	x
CanESM5	Canada	$1.41 \times 1.39^\circ$	x	x	x	x	x	x
EC-Earth3	Europe	$0.7 \times 0.7^\circ$	x	–	x	x	x	x
EC-Earth3-Veg	Europe	$0.7 \times 0.7^\circ$	x	x	x	x	x	x
FGOALS-g3	China	$2 \times 2.03^\circ$	x	x	x	x	x	x
GFDL-ESM4	USA	$1 \times 1^\circ$	x	x	x	x	x	x
GISS-E2-1-G	USA	$2.5 \times 2.5^\circ$	x	x	x	x	x	x
HadGEM3-GC31-LL	UK	$1.88 \times 1.88^\circ$	x	–	x	x	–	x
INM-CM5-0	Russia	$2 \times 1.5^\circ$	x	–	x	x	x	x
IPSL-CM6A-LR	France	$2.5 \times 1.27^\circ$	x	x	x	x	x	x
MIROC-ES2L	Japan	$1.41 \times 1.41^\circ$	x	x	x	x	x	x
MIROC6	Japan	$2.81 \times 2.77^\circ$	x	x	x	x	x	x
MPI-ESM1-2-HR	Germany	$0.94 \times 0.94^\circ$	x	–	x	x	–	x
MRI-ESM2-0	Japan	$1.13 \times 1.13^\circ$	x	x	x	x	x	x
NESM3	China	$1.88 \times 1.88^\circ$	x	–	x	x	–	x

Note: –, Not available.

The second index, the acclimatisation index, is

$$\text{EHI}_{\text{accl}} = \frac{T_i + T_{i+1} + T_{i+2}}{3} - \frac{T_{i-1} + \dots + T_{i-30}}{30} \quad (2)$$

This measures the deviation of the three-day DMT from the average over the prior 30 days, accounting for short-term human and system adaptation. The final EHF is computed as:

$$\text{EHF} = \text{EHI}_{\text{sig}} \times \max(1, \text{EHI}_{\text{accl}}) \quad (3)$$

yielding positive values only when conditions are unusually hot. The resulting values, expressed in $^\circ\text{C}^2$ provide a measure of heatwave intensity. This enables severity classification: Low-intensity for $0 < \text{EHF} < \text{EHF}_{85}$ (where EHF_{85} is the 85th percentile of positive EHF values), severe for $\text{EHF}_{85} \leq \text{EHF} < 3 \times \text{EHF}_{85}$, and extreme for $\text{EHF} \geq 3 \times \text{EHF}_{85}$ allowing normalised comparisons across diverse climates.

Compared to traditional definitions, which rely on sequences of daily maximum temperatures exceeding fixed thresholds (e.g., three days above the 90th percentile) (Perkins 2015; Hobday *et al.* 2016), EHF offers distinct advantages. It incorporates minimum temperatures to capture overnight heat retention and cumulative thermal stress, critical for health impacts, rather than focusing solely on daytime peaks. By including the acclimatisation index, EHF reduces false positives from gradual warming, aligning better with human vulnerability. Additionally, its continuous intensity scale and severity classification provide a more nuanced impact assessment than binary traditional methods, enhancing forecasting accuracy and supporting tailored mitigation strategies (Nairn and Fawcett 2011; Perkins and Alexander 2012). Table 2 presents the grid-cell mean values and ranges of the 85th percentile positive EHF across all models and extreme EHF derived from the observational dataset for 1995–2014.

Table 2 . Gridded-cell average and range of the 85th percentile positive EHF alongside the highest and lowest observed EHF by region (1995–2014 baseline).

Region	85th percentile avg.	85th percentile range	Highest EHF observed range	Lowest observed EHF range
VN	4.91	[0.75, 12.66]	[1.52, 54.31]	[-138.08, -7.24]
R1	6.53	[1.88, 11.28]	[8.19, 37.77]	[-138.08, -84.46]
R2	8.34	[5.53, 12.03]	[12.82, 37.9]	[-112.75, -66.58]
R3	9.19	[5.18, 12.66]	[12.87, 44.34]	[-121.92, -103.5]
R4	8.34	[2.92, 12.66]	[10.35, 54.31]	[-126.88, -65.69]
R5	2.43	[0.87, 4.67]	[3.07, 20.19]	[-74.53, -7.5]
R6	2.48	[0.75, 4.58]	[2.49, 16.62]	[-55.18, -8.09]
R7	1.08	[0.77, 1.48]	[1.52, 8.73]	[-13.31, -7.24]

For the assessment of heatwaves using the EHF method, we evaluate four key characteristics:

- HWI quantified as the annual mean EHF, measures the severity of heatwave events by combining temperature exceedance and acclimatisation effects. This annual mean provides a standardised metric for comparing severity across regions and years.
- Heatwave duration (HWD) is the total number of days across all heatwave events in a year, where each event requires at least three consecutive days with $\text{EHF} > 0$. It is calculated as

$$\text{HWD} = \sum_{j=1}^m d_j \quad (4)$$

where m is the number of heatwave events, and d_j is the number of consecutive days in the j th event. This metric quantifies cumulative heat exposure, crucial for assessing impacts on health, agriculture, and infrastructure (Perkins 2015).

- Heatwave frequency (HWF) is the number of distinct heatwave events in a year, each comprising at least three consecutive days with $\text{EHF} > 0$, separated by at least one day with $\text{EHF} \leq 0$. It is expressed as

$$\text{HWF} = m \quad (5)$$

- Heatwave peak temperature (HWP) is the yearly averaged maximum DMT during heatwave events, calculated as

$$\text{HWP} = \frac{1}{m} \sum_{j=1}^m T_{\max,j} \quad (6)$$

where $T_{\max,j}$ is the maximum DMT during the j th heatwave event.

2.5 Signal to noise ratio

To evaluate the uncertainty of the results, we use the SNR method as proposed by Li and Zhou (2010). This method quantifies uncertainty by comparing the signal (multi-model ensemble mean) to the noise (inter-model variability)

$$\text{SNR} = \frac{\text{Signal}}{\text{Noise}} \quad (7)$$

In our analysis, each scenario is considered equally likely, and within each scenario all climate models are assigned equal weight or probability. This equal-weighting approach is commonly used in multi-model ensemble studies to avoid introducing subjective weighting schemes and allows the ensemble spread to reflect the combined influence of model structural differences and scenario uncertainty. Therefore, each GWL is regarded as the average convergence period across all models and scenarios, with equal weighting applied to each model–scenario combination. We consider the combination of each model and each scenario as a distinct pathway for future projections, and the total number of pathways is represented by n .

The signal is defined as the absolute multi-scenario multi-model ensemble mean (MSMME), representing the central tendency of projections across all n pathways

$$\text{Signal} = \text{MSMME} = \left| \frac{1}{n} \left(\sum x_i \right) \right| \quad (8)$$

where x_i is the value simulated by each pathway i .

The noise quantifies the variability among individual pathways and is calculated as the mean squared deviation from the MSMME

$$\text{Noise} = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \text{MSMME})^2} \quad (9)$$

An SNR greater than 1 indicates higher model agreement and greater confidence in the projections, as the signal (central tendency) is larger than the noise (variability). In this study, the SNR threshold is therefore interpreted as an indicator of the robustness of the projected signal across the ensemble, rather than a strict test of statistical significance. This interpretation is consistent with previous studies that use ensemble spread to assess the emergence and robustness of projected climate signals across multi-model ensembles (e.g., Hawkins and Sutton 2009; Mahlstein *et al.* 2011).

3. Results and discussion

3.1 Validation of CMIP6-VN

The Taylor diagram in figure 2 investigates the seasonal cycle of daily maximum temperature (T_m) from CMIP6-VN models against observed station data for 1995–2014, revealing robust performance with correlation coefficients exceeding 0.99 for most models, indicating strong alignment with observed seasonal patterns. Regionally, northern (R1–R3) and central (R4–R5) Vietnam exhibit superior model accuracy, consistently achieving correlations above 0.99, whereas southern regions (R6–R7) show greater variability, with models like ACCESS-ESM1-5 ($r = 0.98$ in R6, 0.97 in R7) and MRI-ESM2-0 ($r = 0.98$ in R6, 0.97 in R7) recording lower correlations. However, MIROC6, EC-Earth3, HadGEM3-GC31-LL, and INM-CM5-0 maintain correlations above 0.99 across all regions. Despite lower correlations in the south, these regions demonstrate the lowest root mean square errors (RMSE) nationally, ranging from 0.09 mm/day (HadGEM3-GC31-LL, R5) to 0.37 mm/day (ACCESS-ESM1-5, R5), compared to 0.09–0.65 mm/day in central regions (R4–R5) and 0.11–0.67 mm/day in northern regions (R1–R3). Model standard deviations align closely with observations at the national scale, ensuring reliable representation of temperature variability.

The spatial temperature patterns of T_m are equally well captured by CMIP6-VN models, as illustrated in figure 3. All regions except R7 demonstrate exceptional performance with both

median and multi-model ensemble (MME) mean correlations exceeding 0.98, where the convergence of median and MME values coupled with narrow interquartile ranges (IQR) indicates high overall model reliability and consistency. Even in R7, which represents the most challenging region for model accuracy, both median and MME mean correlations remain above 0.95 and show close agreement. While R7 exhibits the highest model dispersion among all regions, this variability remains constrained within a relatively narrow range of 0.94–0.96, demonstrating that even the poorest-performing models in the most difficult region maintain acceptable accuracy levels. The consistently high performance across all regions, combined with low inter-model variability, illustrates the CMIP6-VN dataset as a reliable tool for temperature simulation across Vietnam's diverse climatic zones.

3.2 Process of global warming levels

Figure 4 illustrates the projected timing when GMST anomalies relative to the pre-industrial period (1850–1900) cross critical thresholds of 1.5°C, 2°C, 3°C, and 4°C under different SSP scenarios using CMIP6-VN models listed in table 1. The 1.5°C threshold, representing the ambitious mitigation target of the Paris Agreement (UNFCCC 2015), is projected to be exceeded across all scenarios from SSP1-2.6 to SSP5-8.5. Even under the most ambitious SSP1-1.9 scenario, explicitly designed to limit warming to 1.5°C (IPCC 2018), seven of eleven available models still breach this threshold, with the MME indicating a crossing year of 2027. This outcome underscores the formidable challenge of achieving the 1.5°C goal despite the most ambitious mitigation efforts. Across sustainable development pathways (SSP1-2.6 to SSP2-4.5), all models breach the 1.5°C threshold, with MME crossing years ranging from 2025 (SSP5-8.5) to 2029 (SSP3-7.0), highlighting the narrow window for limiting warming to this level.

The 2°C threshold, previously considered adequate for avoiding severe climate impacts (IPCC 2014), is reached by all models across scenarios except for four of eleven models under SSP1-1.9. MME crossing years range from 2039 (SSP5-8.5) to 2048 (SSP2-4.5), demonstrating that even this higher threshold poses significant implementation challenges. At higher warming levels, the 3°C threshold can potentially be avoided only under the SSP1-2.6 scenario by the end of the 21st century, while 8 of 20 models under the intermediate SSP2-4.5 scenario cross this level around 2071. Under

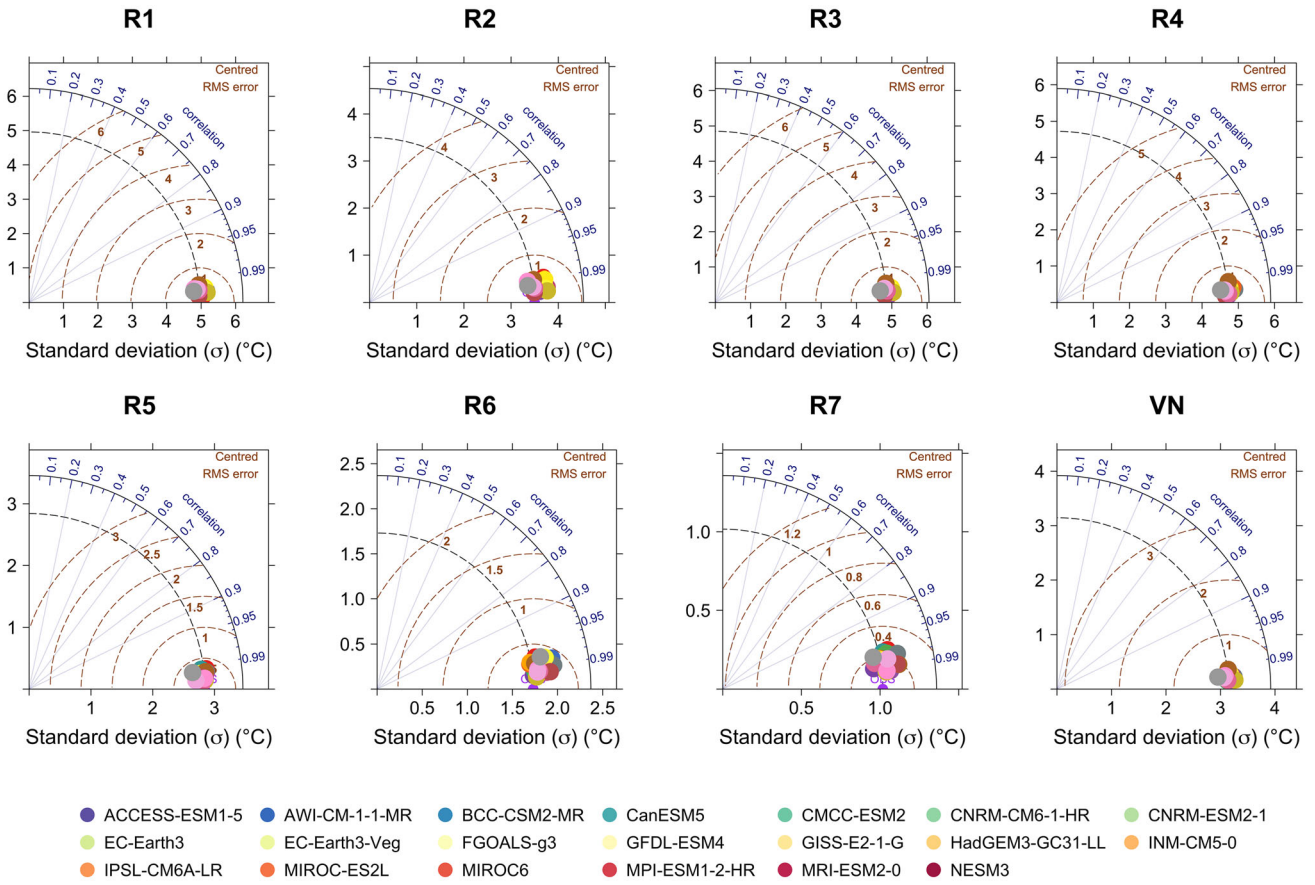


Figure 2. Taylor diagram showing the seasonal cycle statistics of T_m over the 1995–2014 period for CMIP6-VN models, with each dot representing a model and the observation indicated by the purple reference point on the x-axis.

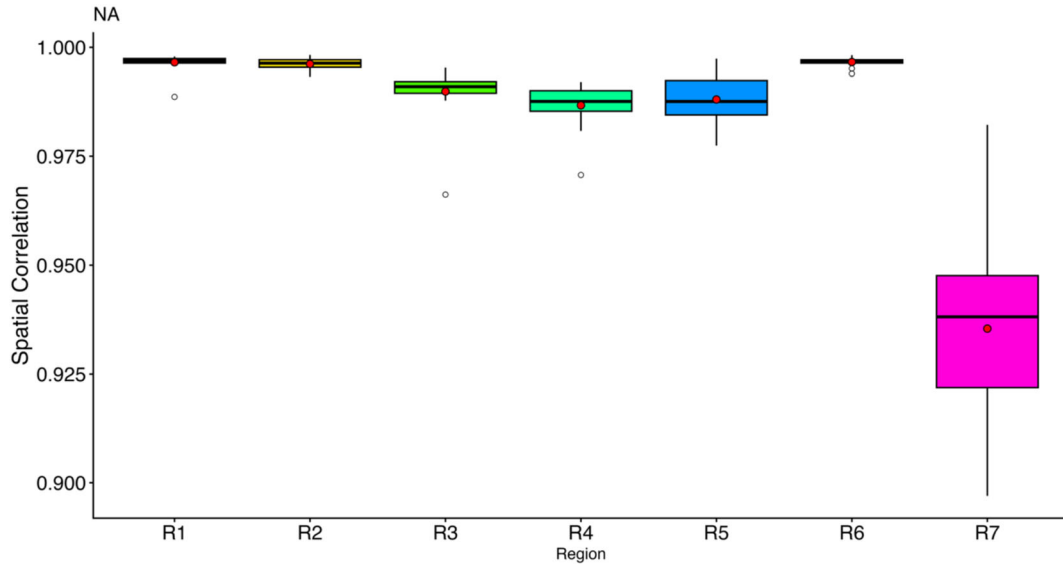


Figure 3. Spatial correlation between CMIP6-VN models and observations for climatology (1995–2014) across seven climate regions in Vietnam. Boxplots show the distribution of correlation coefficients between each model and observations in each region. Boxes indicate the interquartile range (IQR), the line marks the median, and whiskers extend to $1.5 \times \text{IQR}$. White dots represent model outliers beyond $3 \times \text{IQR}$. Red dots show the multi-model ensemble mean correlation.

higher emission pathways (SSP3-7.0 and SSP5-8.5), the 3°C level, associated with widespread severe impacts (IPCC 2014), is surpassed around

2068 and 2062, respectively. The extreme 4°C threshold, projected to trigger catastrophic global consequences, is reached under high (SSP3-7.0)

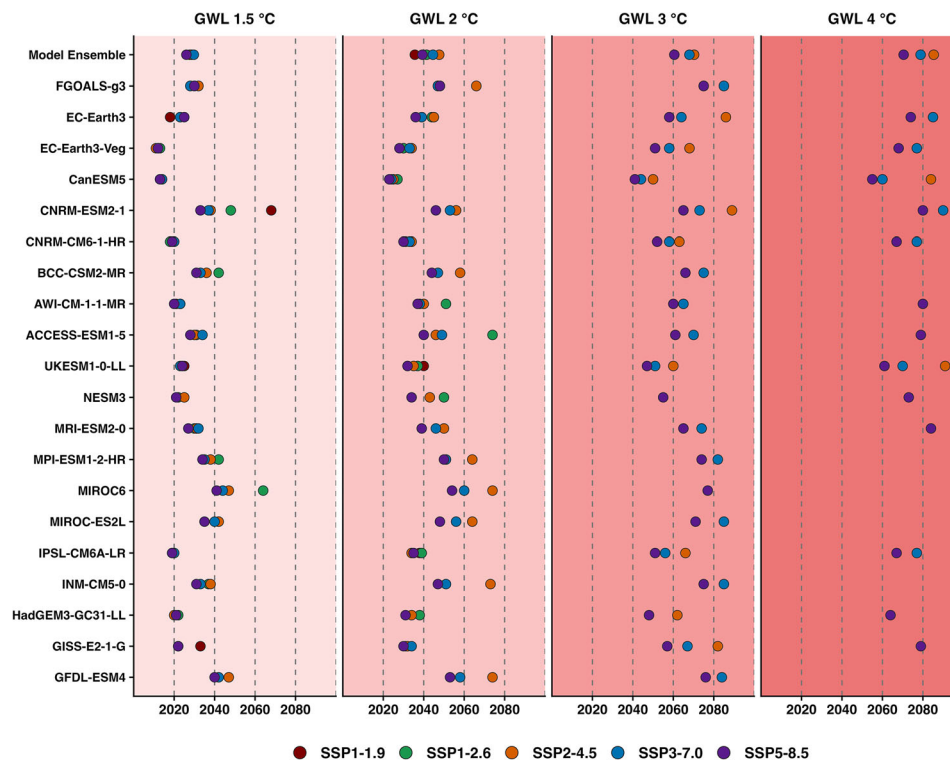


Figure 4. Projected years when GMST crosses 1.5°C, 2°C, 3°C, and 4°C thresholds for each of the 33 CMIP6 models under scenarios SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Black crosses represent the MME crossing times for each threshold.

and very high (SSP5-8.5) emission scenarios, with MME crossing times around 2079 and 2073, respectively. Notably, 10 of 17 under SSP3-7.0 and 14 of 20 models under SSP5-8.5 exceed this threshold, emphasising the substantial risks of unmitigated emissions.

CMIP6 models offer improved process representation and higher spatial resolution compared to CMIP5, though they exhibit a wider range of climate sensitivity values, with some ‘hot’ models projecting accelerated warming beyond IPCC AR6’s ‘likely’ or ‘very likely’ ranges. Relying solely on ensemble means, as in earlier IPCC assessments, may overestimate future climate changes. To address this, we adopt the IPCC AR6 framework and followed Hausfather *et al.* (2022) by using GWLs instead of time-based scenarios, better reflecting the stronger correlation of climate impacts (e.g., temperature and precipitation changes) with warming magnitude rather than timing or emission pathways (IPCC 2021). GWL timing can be derived from IPCC projections, while ‘hot’ models are retained to assess tail risks and worst-case scenarios, given that high climate sensitivity remains plausible. All selected CMIP6 models are treated with equal weight in the

ensemble, and no model filtering based on climate sensitivity is applied. Consequently, the ensemble spread reflects the full range of structural differences among models, including those with higher climate sensitivity. The use of GWLs partially mitigates the influence of such models on projected impacts by aligning model outputs according to warming levels rather than simulation time, allowing results to be interpreted primarily in relation to the magnitude of global warming rather than differences in model sensitivity.

3.3 Evolution of extreme heatwave under global warming levels

The analysis of heatwave characteristics across Vietnam reveals significant shifts as GWLs increase (figure 5). Even a ‘modest’ increase in warming from 1.5°C to 2°C leads to substantial changes in heatwave extremes, with both intensity and duration increasing dramatically across Vietnam. By mid-century, when the 2°C GWL could be reached under current policies (UNEP 2024), the likely range (interquartile range, 25–75th percentile) of HWI increase is projected to be 0–0.7°C² nationally. At 3°C GWL, which could be reached

by the end of the century under current policies, HWI is projected to increase significantly by $0.3\text{--}1.3^{\circ}\text{C}^2$. Under the most severe scenario of 4°C GWL, HWI is likely to rise by $0.7\text{--}1.8^{\circ}\text{C}^2$, representing a substantial departure from historical norms. Duration of heatwaves increases significantly alongside HWI. At 2°C GWL, HWD nationally increases by $15.9\text{--}30.4$ days annually, escalating dramatically to $81.6\text{--}121.5$ days at 4°C GWL. While the North Central region (R4) is expected to experience the smallest HWD increase ($52.5\text{--}80.9$ days under 4°C GWL), the Southern region (R7) faces the most severe impact

($109.1\text{--}168.3$ days under 4°C GWL), with heatwave days potentially occupying nearly half the year and creating unprecedented heat stress conditions. Heatwave frequency and peak temperature also show substantial increases as global warming intensifies. At the most severe condition of 4°C GWL, compared to the reference period, HWF and HWP may increase by a national average of $8.1\text{--}9.5$ events and $0.7\text{--}1.3^{\circ}\text{C}$, respectively, indicating more frequent and intense extreme heat episodes.

Spatial variations of heatwave characteristics over Vietnam are notably pronounced, with

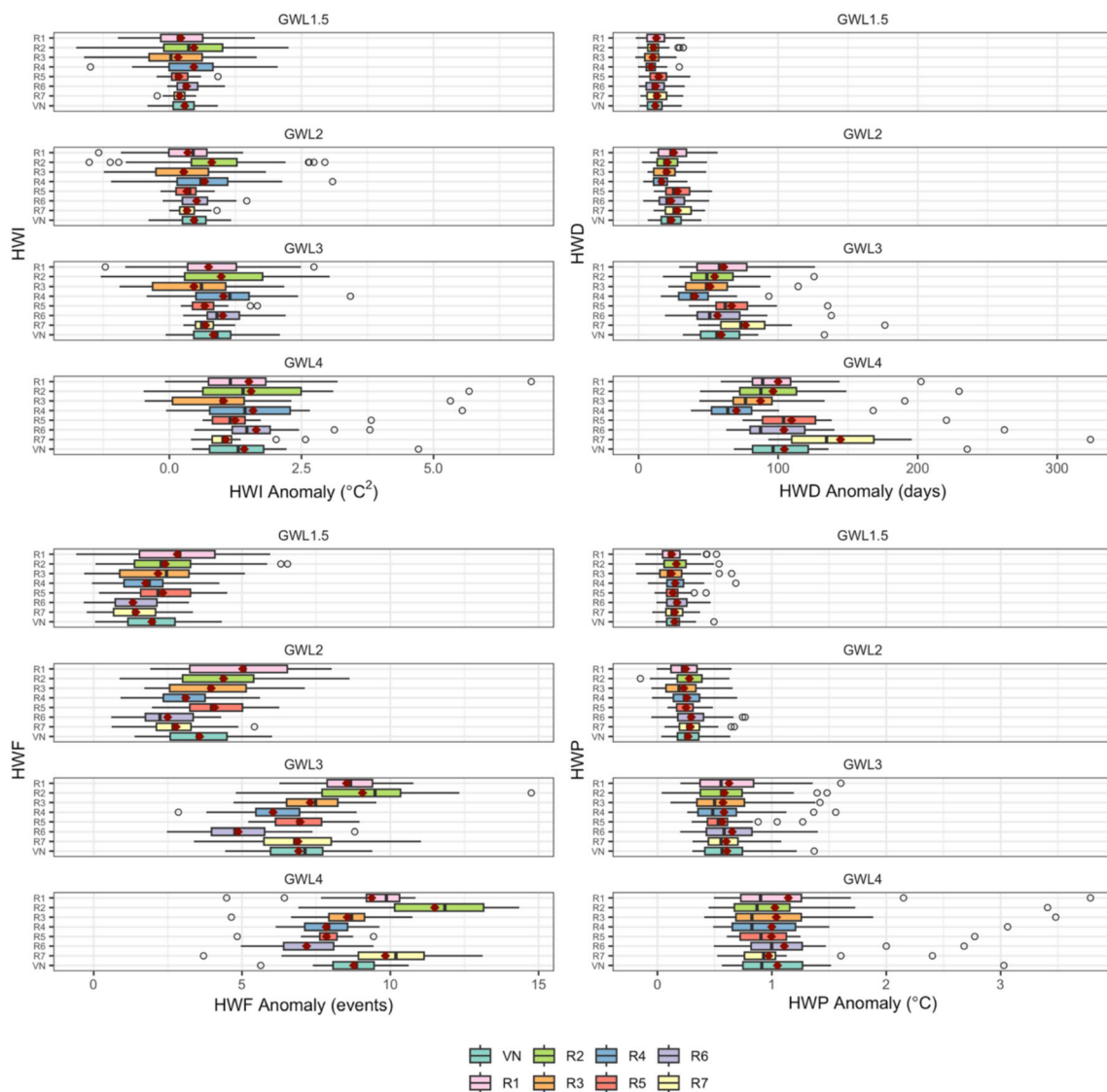


Figure 5. Projected changes of HWI, HWD, HWF and HWP over Vietnam and its seven sub-climatic regions, relative to the 1995–2014 baseline period, under GWLs 1.5°C , 2°C , 3°C , and 4°C . Boxplots illustrate the distribution of spatial correlation coefficients between each model and observations within each region. Boxes represent the IQR, the central line indicates the median, and whiskers extend to values within $1.5 \times \text{IQR}$. Outlier models exceeding $3 \times \text{IQR}$ are shown as white dots. Red dots mark the MME mean correlation for each region.

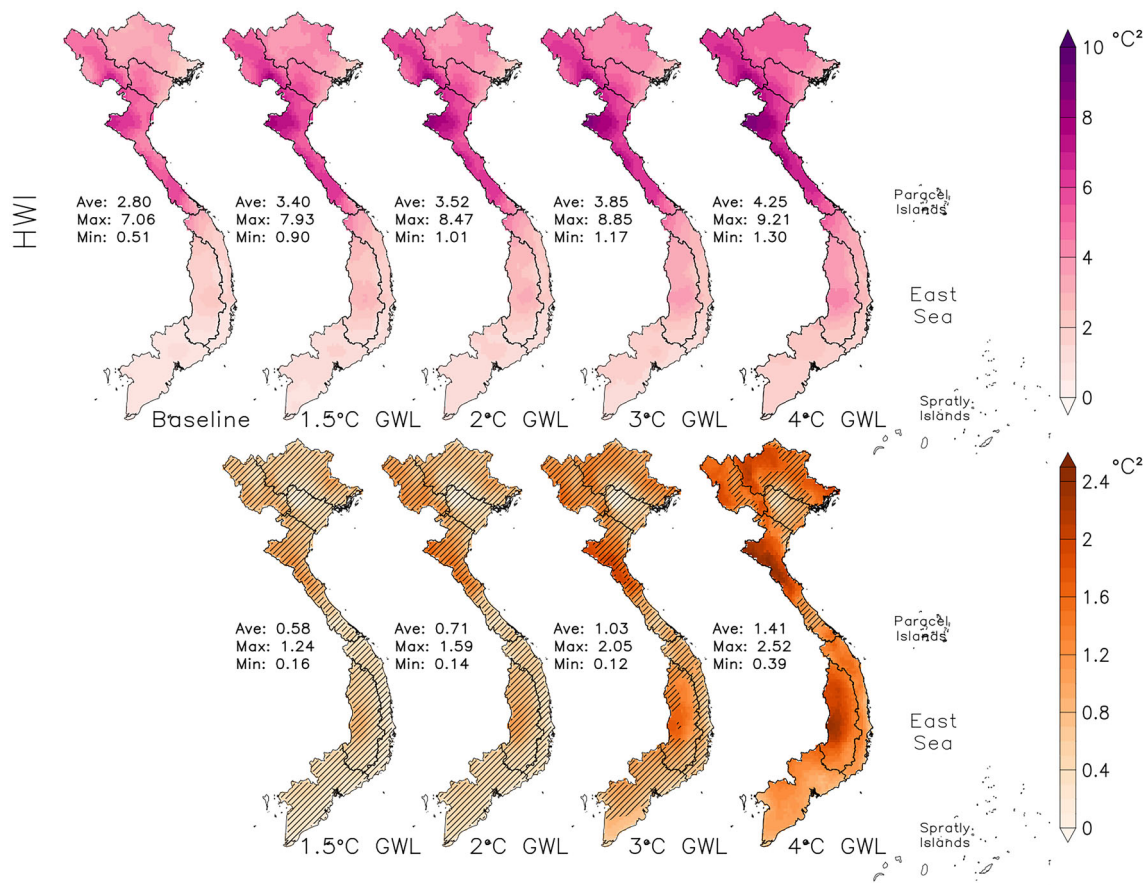


Figure 6. Spatial patterns of projected changes in 21-year mean of HWI over Vietnam under different global warming levels (GWLs) by MSMME. Top panels show projected temperature at each GWL, and bottom panels show their anomalies relative to the 1995–2014 baseline. Hatched areas indicate regions where the SNR < 1, indicating low model agreements.

northern and southern regions experiencing different patterns of change. In the northern regions (R1–R4), HWI, HWF, and HWP tend to increase more rapidly than in the southern regions (R5–R7), suggesting heightened vulnerability to heat extremes. Conversely, HWD increases more substantially in the southern regions than in the north, reflecting regional differences in heat persistence patterns. Model variability increases under higher GWLs, particularly beyond 3°C warming, reflecting greater uncertainty in extreme future projections and highlighting the importance of robust adaptation planning across a range of potential outcomes.

With global temperature rise, national HWI averages increase from 2.80°C^2 in the baseline period (1995–2014) to 4.25°C^2 at 4°C GWL, with anomalies escalating from 0.58°C^2 at 1.5°C GWL to 0.71°C^2 at 2°C GWL, 1.03°C^2 at 3°C GWL, and 1.41°C^2 at 4°C GWL, demonstrating a progressive intensification pattern (figure 6). Northern regions (R1–R4) experience the most severe heatwave

intensities, averaging 5.9°C^2 and peaking at 6.5°C^2 in R2 at 4°C GWL, while southern regions (R5–R7) reach an average of 2.7°C^2 with a minimum of 1.9°C^2 in R7 (table 3), establishing a pronounced latitudinal gradient in heatwave severity. Although R6 has the lowest absolute HWI across all GWLs (2.13°C^2 at 1.5°C GWL to 3.2°C^2 at 4°C GWL), it shows the steepest increase (0.59 – 1.6°C^2), closely followed by R4 (0.79 – 1.58°C^2). This pattern suggests that regions with initially moderate heatwave intensities may experience disproportionately rapid escalation under higher warming scenarios.

Nationally, the HWI anomaly increase displays non-linear characteristics, with a relatively modest rise from 2°C to 3°C GWL (0.71 – 1.03°C^2) contrasting sharply with the accelerated increase from 3°C to 4°C GWL (1.03 – 1.41°C^2). This threshold effect indicates that heatwave impacts intensify disproportionately at higher warming levels, revealing a critical tipping point that has not been fully characterised in previous regional

Table 3. Projected changes in heatwave extreme indices in Vietnam and in the seven sub-climatic regions, for different GWLs.

GWLs	Region	HWI ($^{\circ}\text{C}^2$)*	HWD (days)	HWF (events)	HWP ($^{\circ}\text{C}$)
GWL1.5	VN	3.4 (+0.6 $\pm$ 1.7)	28.2 (+14.5 $\pm$ 15.3)	5.7 (+2 $\pm$ 1.2)	34.6 (+0.3 $\pm$ 0.6)
	R1	4 (+0.6 $\pm$ 2.2)	27.2 (+15.4 $\pm$ 15.7)	6.9 (+2.8 $\pm$ 1.7)	34 (+0.3 $\pm$ 0.8)
	R2	5.6 (+0.8 $\pm$ 1.8)	26.6 (+13.9 $\pm$ 17.3)	6.3 (+2.4 $\pm$ 1.5)	32.3 (+0.3 $\pm$ 0.6)
	R3	5 (+0.6 $\pm$ 2.3)	25.6 (+12.9 $\pm$ 15)	6.3 (+2.2 $\pm$ 1.3)	35.6 (+0.3 $\pm$ 0.9)
	R4	5.9 (+0.8 $\pm$ 2)	24.4 (+11.5 $\pm$ 14.4)	5.7 (+1.8 $\pm$ 1.1)	36.4 (+0.3 $\pm$ 0.7)
	R5	2.2 (+0.4 $\pm$ 1.1)	31.2 (+17.2 $\pm$ 16.3)	6 (+2.3 $\pm$ 1.2)	34.9 (+0.2 $\pm$ 0.5)
	R6	2.1 (+0.6 $\pm$ 1.4)	29.6 (+14.8 $\pm$ 16)	4.9 (+1.4 $\pm$ 1)	33.9 (+0.3 $\pm$ 0.6)
GWL2	R7	1.2 (+0.4 $\pm$ 1.1)	30.6 (+15 $\pm$ 13.3)	4.4 (+1.4 $\pm$ 1)	35.3 (+0.2 $\pm$ 0.5)
	VN	3.5 (+0.7 $\pm$ 1.6)	38.8 (+25.2 $\pm$ 15.1)	7.2 (+3.5 $\pm$ 1.5)	34.7 (+0.4 $\pm$ 0.6)
	R1	4 (+0.7 $\pm$ 2.1)	38.7 (+27 $\pm$ 16.5)	9.1 (+5 $\pm$ 1.9)	34 (+0.4 $\pm$ 0.8)
	R2	5.9 (+1.1 $\pm$ 1.8)	35.5 (+22.8 $\pm$ 16.2)	8.2 (+4.3 $\pm$ 1.9)	32.4 (+0.4 $\pm$ 0.6)
	R3	5 (+0.6 $\pm$ 2.1)	34.6 (+22 $\pm$ 15.1)	8 (+3.9 $\pm$ 1.6)	35.6 (+0.4 $\pm$ 0.8)
	R4	6.1 (+0.9 $\pm$ 2)	31.3 (+18.4 $\pm$ 13.7)	7.1 (+3.1 $\pm$ 1.3)	36.4 (+0.4 $\pm$ 0.7)
	R5	2.3 (+0.5 $\pm$ 1.1)	43.8 (+29.7 $\pm$ 15.4)	7.7 (+4 $\pm$ 1.3)	35 (+0.3 $\pm$ 0.5)
GWL3	R6	2.3 (+0.7 $\pm$ 1.3)	39.8 (+25 $\pm$ 15.7)	6 (+2.5 $\pm$ 1.2)	34 (+0.4 $\pm$ 0.5)
	R7	1.3 (+0.5 $\pm$ 1)	44.4 (+28.8 $\pm$ 13.5)	5.7 (+2.7 $\pm$ 1.3)	35.4 (+0.4 $\pm$ 0.5)
	VN	3.9 (+1 $\pm$ 1.5)	73.7 (+60 $\pm$ 22.1)	10.5 (+6.8 $\pm$ 1.6)	35 (+0.7 $\pm$ 0.6)
	R1	4.3 (+1 $\pm$ 1.9)	73.7 (+62 $\pm$ 22.3)	12.5 (+8.4 $\pm$ 1.5)	34.4 (+0.7 $\pm$ 0.7)
	R2	6.1 (+1.2 $\pm$ 1.9)	68.4 (+55.8 $\pm$ 22.9)	12.7 (+8.9 $\pm$ 2.5)	32.7 (+0.7 $\pm$ 0.7)
	R3	5.1 (+0.7 $\pm$ 2)	64.8 (+52.2 $\pm$ 20.6)	11.4 (+7.2 $\pm$ 1.5)	36 (+0.7 $\pm$ 0.7)
	R4	6.4 (+1.3 $\pm$ 1.8)	54.6 (+41.7 $\pm$ 17.8)	10 (+6 $\pm$ 1.5)	36.7 (+0.7 $\pm$ 0.7)
GWL4	R5	2.6 (+0.8 $\pm$ 1)	81.7 (+67.6 $\pm$ 20.2)	10.6 (+6.8 $\pm$ 1.3)	35.3 (+0.6 $\pm$ 0.5)
	R6	2.7 (+1.2 $\pm$ 1.3)	72.2 (+57.4 $\pm$ 23.5)	8.3 (+4.8 $\pm$ 1.5)	34.3 (+0.7 $\pm$ 0.6)
	R7	1.6 (+0.8 $\pm$ 1)	92 (+76.3 $\pm$ 25.3)	9.8 (+6.8 $\pm$ 1.9)	35.7 (+0.7 $\pm$ 0.5)
	VN	4.3 (+1.4 $\pm$ 1)	118.1 (+104.4 $\pm$ 37.7)	12.5 (+8.8 $\pm$ 1.7)	35.4 (+1 $\pm$ 0.5)
	R1	4.9 (+1.5 $\pm$ 1.5)	111.6 (+100 $\pm$ 31.8)	13.5 (+9.4 $\pm$ 1.6)	34.9 (+1.1 $\pm$ 0.7)
	R2	6.5 (+1.5 $\pm$ 1.4)	109 (+96.3 $\pm$ 39.8)	15.4 (+11.5 $\pm$ 2.1)	33.1 (+1 $\pm$ 0.6)
	R3	5.4 (+1 $\pm$ 1.3)	99.9 (+87.3 $\pm$ 32.2)	12.7 (+8.6 $\pm$ 1.5)	36.3 (+1 $\pm$ 0.7)
	R4	6.7 (+1.6 $\pm$ 1.3)	82.9 (+70 $\pm$ 28.4)	11.8 (+7.8 $\pm$ 1.2)	37.1 (+1 $\pm$ 0.6)
	R5	3 (+1.2 $\pm$ 0.7)	123.7 (+109.6 $\pm$ 31.6)	11.6 (+7.8 $\pm$ 1.1)	35.7 (+1 $\pm$ 0.5)
	R6	3.2 (+1.6 $\pm$ 0.8)	119 (+104.2 $\pm$ 42)	10.7 (+7.2 $\pm$ 1.6)	34.7 (+1.1 $\pm$ 0.5)
	R7	1.9 (+1.1 $\pm$ 0.5)	160.3 (+144.7 $\pm$ 51.1)	12.8 (+9.8 $\pm$ 2.5)	36 (+1 $\pm$ 0.4)

*All unit, for instance, $^{\circ}\text{C}$ (change in $^{\circ}\text{C} \pm 1\text{STD}$), represents the projected temperature value and its deviation from a baseline in $^{\circ}\text{C}$, with $\pm 1\text{STD}$ indicating the standard deviation (model uncertainty). For example, 34.6 (+0.3 $\pm$ 0.6) means the projected temperature is 34.6 $^{\circ}\text{C}$, with an increase of +0.3 $^{\circ}\text{C}$ and an uncertainty range of $\pm 0.6^{\circ}\text{C}$.

assessments. Model agreement for HWI projections is initially weak at 1.5 $^{\circ}\text{C}$ and 2 $^{\circ}\text{C}$ GWL but strengthens progressively at 3 $^{\circ}\text{C}$ GWL, particularly in the R6 region. At 4 $^{\circ}\text{C}$ GWL, model consensus becomes robust, especially across southern regions, with SNR values consistently exceeding 1, indicating high confidence in the projected heatwave intensification patterns.

Figure 7 reveals a sharp increase in HWD as global warming intensifies, with Vietnam facing unprecedented levels of heat exposure under all scenarios. Annual HWD averages increase exponentially from the 1995–2014 baseline of 13.6 days, doubling to 28.1 days under 1.5 $^{\circ}\text{C}$ GWL, nearly tripling to 38.8 days under 2 $^{\circ}\text{C}$ GWL, and reaching

alarming levels of 73.6 days (5.4 times baseline) under 3 $^{\circ}\text{C}$ GWL. At 4 $^{\circ}\text{C}$, HWD reaches 118 days per year, nearly one-third of the year, representing an 8.7-fold increase. Regional disparities in heatwave exposure are pronounced and will intensify with warming. Southern regions (R5–R7), which already experience longer HWD than northern areas (R1–R4), will face accelerated increases in heat exposure. Under 4 $^{\circ}\text{C}$ GWL, northern regions are projected to experience 101 HWD days (an 88-day increase), while southern regions face 134 days (a 119-days increase). The southernmost region (R7) emerges as the most vulnerable, with average HWD reaching 160 days under 4 $^{\circ}\text{C}$ warming. In extreme cases, some areas within R7

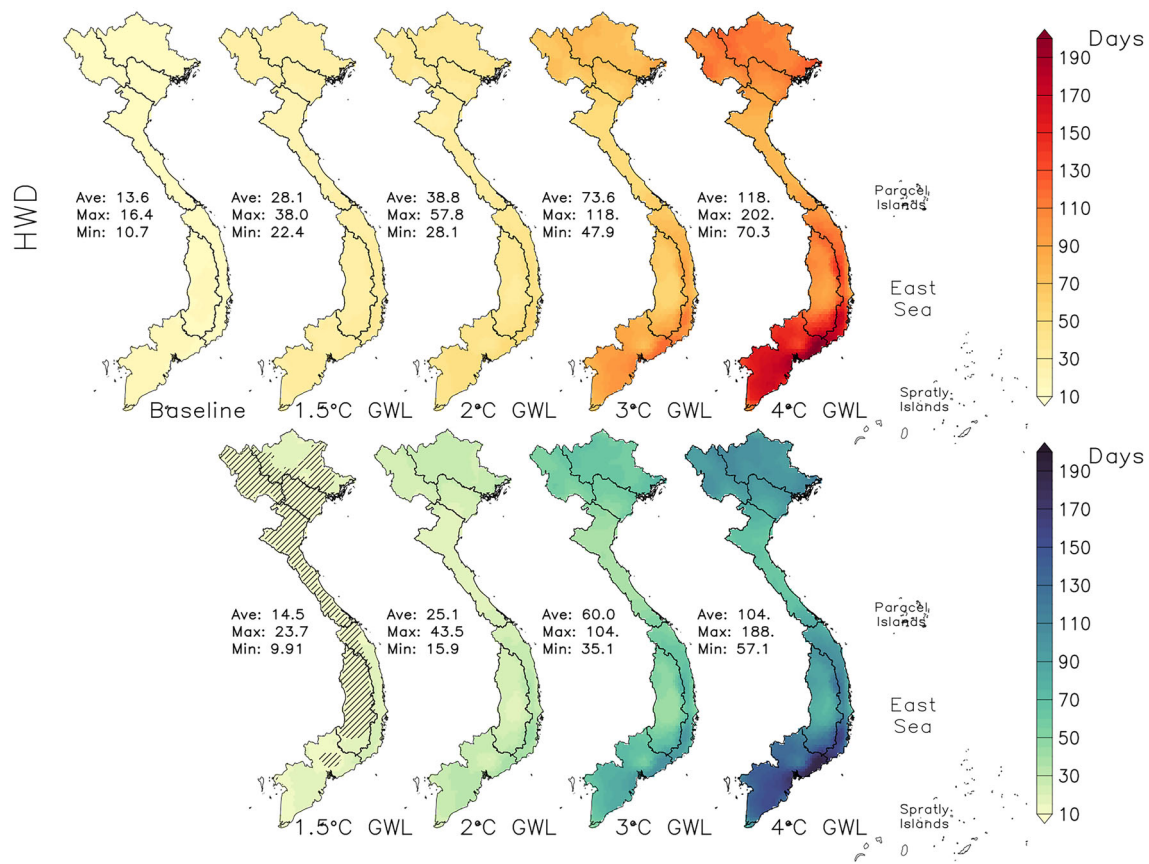


Figure 7. Spatial patterns of projected changes in the 21-year mean HWD over Vietnam under different GWLs based on the MSMME. Top panels show projected values at each GWL, while bottom panels show anomalies relative to the 1995–2014 baseline. Hatched areas indicate regions where $SNR < 1$.

may experience over 200 HWD days, effectively creating year-round hot conditions. Model confidence varies by region and scenario. Except for R7, model agreement is weak at 1.5°C but strengthens markedly from 2°C onward nationwide, supporting the credibility of these projections for climate policy and adaptation planning.

As Vietnam faces rising temperatures across all GWLs, the frequency of heatwave events is projected to increase significantly. MSMME results show that HWF rises from a baseline of 3.7 events to 5.7 at 1.5°C GWL, 7.2 at 2.0°C, 10.5 at 3.0°C, and peaks at 12.4 events per year under 4.0°C warming (figure 8). While HWD increases more rapidly in the southern regions (figure 7), the north consistently experiences a higher number of heatwave events. From 2.0°C to 4.0°C GWL, average HWF in the north increases from 8.1 to 13.3 events, compared to an increase from 6.5 to 11.7 events in the south (table 3). This suggests that although heatwaves are less frequent in the south, each event tends to last longer. Strong model agreement across all regions and warming levels,

indicated by positive SNR value from 1.5°C onward, demonstrates robust confidence in projected HWF increases and supports reliable climate risk assessment for adaptation planning.

Peak heatwave temperature HWP increases with heatwave duration and frequency but at a slower rate than overall global warming (figure 9). Nationally, HWP rises by 0.27°C at 1.5°C GWL, 0.36°C at 2°C, 0.68°C at 3°C, and 1.04°C at 4°C compared to the baseline. The North Central region (R4) records the highest HWP, reaching 37°C under 4°C warming, with localised peaks up to 39.1°C. Regional differences in HWP are small but consistent, with northern areas experiencing slightly greater increases than the south, north-south differences range from 0.01°C (2°C GWL) to 0.03°C (1.5°C GWL). This indicates a relatively uniform intensification of peak heat across the country. Model agreement on HWP trends is weak at 1.5°C and 2°C GWL but improves significantly in southern regions at 3°C and becomes strong nationwide at 4°C. These results suggest modest HWP increases by mid-century, followed by more

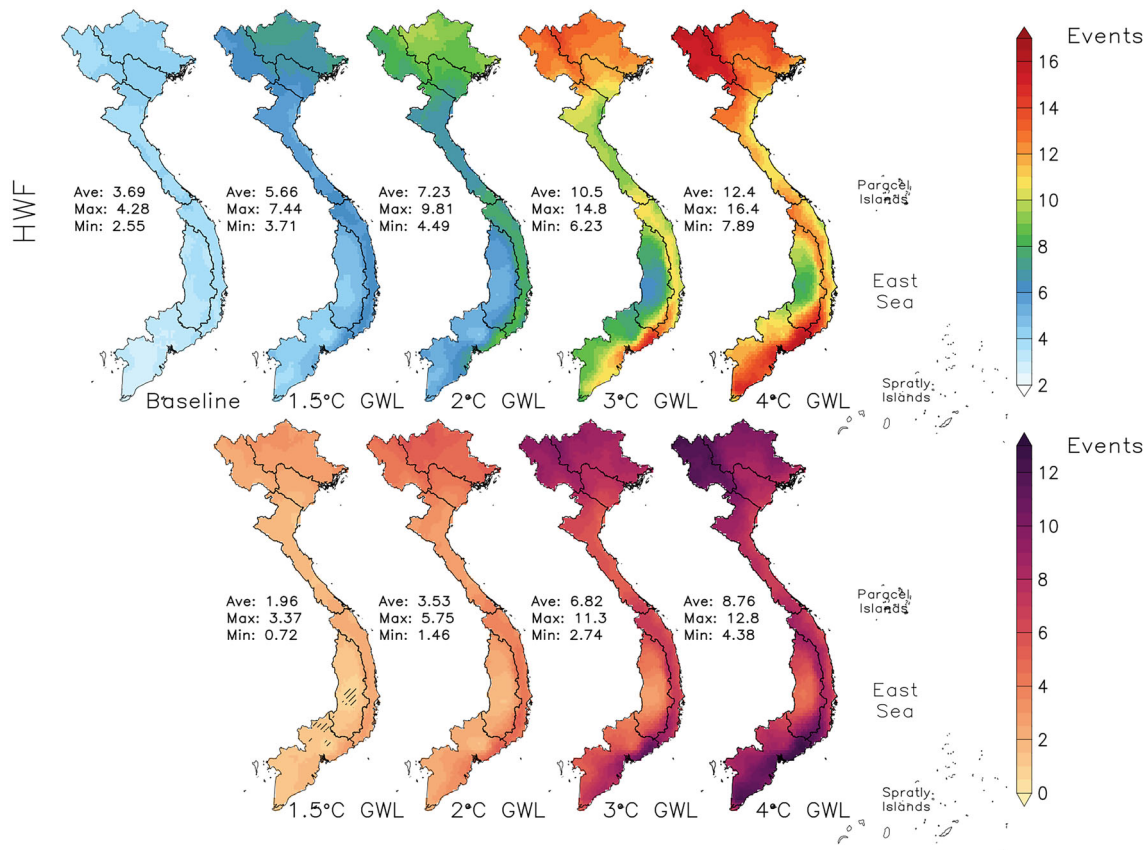


Figure 8. Spatial patterns of projected changes in the 21-year mean HWF over Vietnam under different GWLs based on the MSMME. Top panels show projected values at each GWL, while bottom panels show anomalies relative to the 1995–2014 baseline. Hatched areas indicate regions where SNR < 1.

substantial and reliable intensification toward the century's end.

Figure 10 illustrates the time evolution of HWI, HWD, HWF, and HWP based on CMIP6-VN projections across all SSP scenarios, using 21-year periods centered around each GWL. Since each model reaches a given GWL at a different time, we aligned all simulations to a common time frame – from Year 1 (Y1) to Year 21 (Y21) – to enable consistent comparison. HWI patterns reveal distinct north-south contrasts throughout all warming levels. Northern regions show greater year-to-year variability and consistently higher HWI values than southern areas. The increasing trend with rising GWLs is only clearly evident at 4°C warming, consistent with low model agreement at lower GWLs (figure 6). This regional difference reflects Vietnam's climate gradient – northern areas experience pronounced seasonal contrasts (hot summers, cold winters), while southern regions maintain more stable year-round heat. Consequently, rising temperatures amplify HWI more dramatically in northern Vietnam's broader

temperature range. HWD and HWF show clear increasing trends across all GWL periods but with contrasting regional patterns. Southern regions face longer heatwave durations, while northern areas experience higher frequency increases. At 4°C GWL, HWD maintains its increasing pace, but HWF increases become less pronounced across all regions compared to the 1.5–3°C GWL periods, suggesting a potential stabilisation in heatwave frequency under extreme warming scenarios. HWP shows clear increases between GWL periods, with progressively hotter peak temperatures at higher warming levels. However, the rate of HWP increase is modest compared to the magnitude of global temperature changes, and remains relatively consistent across all regions throughout each GWL period. At the national level, Vietnam exhibits average increases in all indices, but these averages mask substantial regional heterogeneity.

Model projections exhibit reduced annual variability within each GWL period compared to baseline conditions, but inter-model uncertainty increases substantially with rising GWLs. This

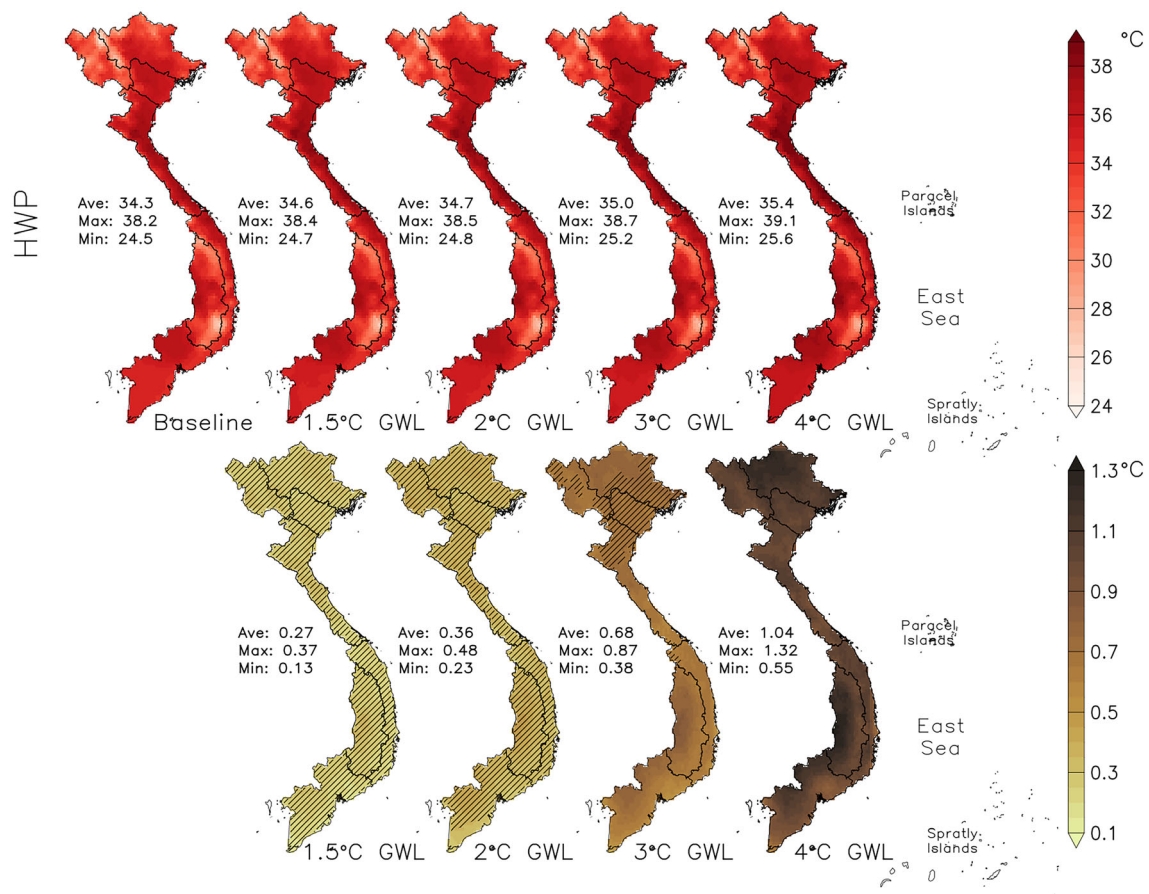


Figure 9. Spatial patterns of projected changes in the 21-year mean HWP over Vietnam under different GWLs based on the MSMME. Top panels show projected values at each GWL, while bottom panels show anomalies relative to the 1995–2014 baseline. Hatched areas indicate regions where $SNR < 1$.

growing uncertainty reflects the challenge of projecting extreme temperature events under unprecedented warming conditions.

4. Conclusion

This study provides the first comprehensive analysis of heatwave trends in Vietnam under escalating GWLs from 1.5°C to 4°C, utilising the high-resolution CMIP6-VN dataset and the EHF methodology. By analysing four key heatwave characteristics—intensity (HWI), duration (HWD), frequency (HWF), and peak temperature (HWP) – across seven sub-climatic regions using 20 CMIP6-VN models and scenarios (historical, SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5), we quantify spatiotemporal variations in extreme heat exposure. Validation against observed data from 146 meteorological stations (1995–2014) confirms model reliability, with correlation coefficients exceeding 0.98 and low root mean square errors.

The results reveal dramatic intensification of heatwave characteristics with progressive warming, following a non-linear escalation pattern particularly beyond 3°C. Nationally, HWI increases from baseline 2.80°C^2 to 4.25°C^2 at 4°C GWL, with anomalies rising exponentially from 0.58°C^2 at 1.5°C to 1.41°C^2 at 4°C. Even under the Paris Agreement’s ambitious 1.5°C target, Vietnam faces significant impacts: intensity rises by 0.6°C^2 , duration extends by 14.5 days annually, frequency increases by 2 events per year, and peak temperatures rise by 0.3°C . Under catastrophic 4°C warming, HWD shows exponential growth from baseline 13.6 days to 118 days (8.7-fold increase), while HWF increases from 3.7 to 12.4 events annually, and HWP rises by 1.04°C nationally, peaking at 37°C in central regions.

Critical regional disparities emerge along a pronounced latitudinal gradient. Northern regions (R1–R4) experience more frequent and intense heatwaves, with R2 reaching up to 15.4 events

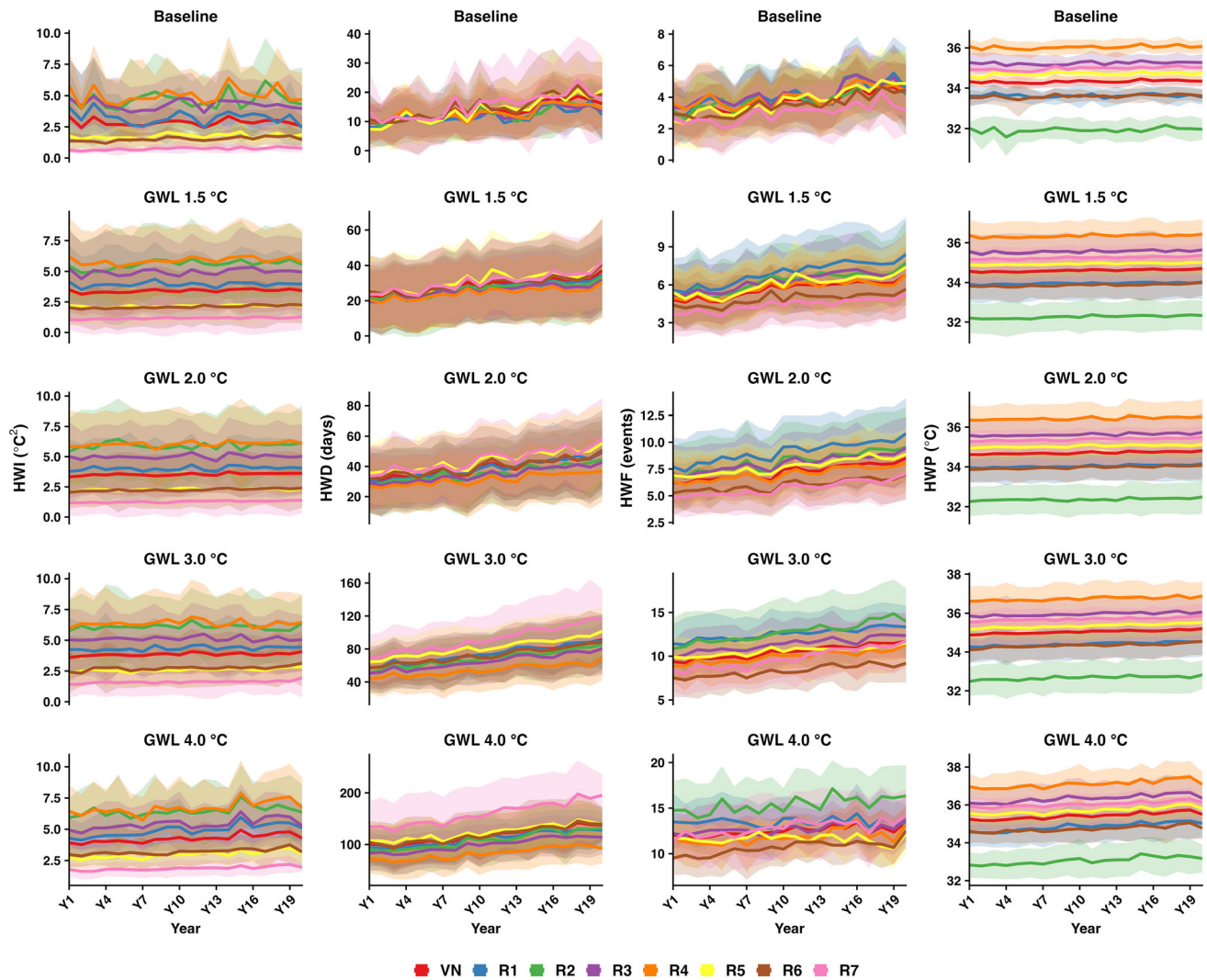


Figure 10. Time evolution of regional heatwave characteristics – Heatwave Intensity (HWI), Duration (HWD), Frequency (HWF), and Peak Temperature (HWP) – under 1.5–4°C global warming levels, based on 21-year annual projections from the CMIP6-VN model ensemble across all SSP scenarios. Solid lines represent the MSMME simulations for each region (R1–R7) and the national average (VN). Shaded areas of the same color indicate the model uncertainty range (± 1 standard deviation).

annually under 4°C warming, while southern regions (R5–R7) face prolonged heat exposure. The southernmost region (R7) is most vulnerable, potentially experiencing over 160 heatwave days annually under 4°C warming – nearly half the year under extreme heat conditions. Temporal analysis reveals that the 1.5°C threshold will be exceeded by 2025–2029 across most scenarios, already breached in 2024 at 1.55°C, while the catastrophic 4°C level could be reached by 2073–2079 under high-emission pathways.

By applying the IPCC-endorsed GWL framework, this study assesses impacts independent of emission scenarios and addresses uncertainties from high-sensitivity models. SNR analysis shows increasing inter-model agreement at higher GWLs (SNR > 1 for key metrics at 4°C), enhancing

confidence in the projections. These findings underscore Vietnam's acute vulnerability due to its coastal geography, densely populated deltas, and climate-sensitive economy. The high-resolution results bridge global climate signals and local risk, offering a robust scientific basis for prioritising targeted mitigation, strengthening adaptation strategies, and informing policy at both national and regional levels.

Authors statement

QTA conceptualised the study, performed the simulations, analysed the data, and drafted the initial manuscript. NNTH, WSWMJ, NAAB, and

OCG contributed to the interpretation of the results. All authors reviewed and approved the final version of the manuscript.

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