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RESEARCH

Changes in temperature and rainfall extremes in Vietnam under progressive global warming levels from 1.5 °C to 4 °C

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Abstract
This study analyzes projected climate extremes in Vietnam using 33 statistically downscaled CMIP6 models (CMIP6-VN database) across global warming levels (GWLs) from 1.5 °C to 4 °C, revealing significant regional variations in temperature and precipitation patterns. Temperature analyses demonstrate substantial warming trends compared to the baseline period 1995–2014: with northern regions (R1-R4) experiencing larger temperature increases—approximately 0.6 °C higher at 1.5 °C GWL and up to 1 °C higher at 4 °C GWL compared to southern regions (R5-R7). The annual percentage of warm days (TX90p) could dramatically increase from 25.5% at 2 °C GWL to 57.5% at 4 °C GWL. Southern regions, particularly the Mekong Delta and Southeast, face the most severe heat. At 4 °C GWL, these areas may experience many hot days (daily maximum temperature TX≥35 °C), potentially reaching 220 days per year. Precipitation projections show high uncertainty due to large inter-model spread. Maximum 1-day precipitation (Rx1day) is projected to increase moderately, ranging from 8.9% at 2 °C GWL to 13.8% at 4 °C GWL, with the North Central Region experiencing the largest increases (up to 15.1% at 4 °C GWL). Changes in the frequency of heavy precipitation days (≥50 mm and ≥100 mm) are minimal and statistically insignificant across all regions and GWLs. Notably, the annual maximum number of consecutive dry days (CDD) is projected to increase across regions, with the southern areas experiencing the longest durations (up to 86 days) and the most substantial increases (up to 11.6 days at 4 °C GWL) among all sub-climatic regions. The study emphasizes the urgent need for flexible, targeted adaptation strategies to mitigate potential consequences, agriculture, water resources, and economic productivity, highlighting the critical importance of reducing greenhouse gas emissions.

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1 Introduction

Climate change is a critical global issue, with recent years experiencing unprecedented temperature rises (WMO, 2023). Research identifies human activities, particularly the anthropogenic increase in atmospheric greenhouse gas emissions, as the primary driver of this warming (IPCC, 2021a). Observations over the past century indicate that the global mean surface temperature (GMST) has risen by approximately 1.09 °C [0.95–1.2 °C] over 2011–2020 compared to pre-industrial levels. Moreover, the rate of warming has accelerated in recent decades, with global surface temperature rising by approximately 0.2 °C per decade since the 1980 s, compared to an average increase of about 0.07 °C per decade over the 20th century. This acceleration has caused profound changes in the climate system (IPCC, 2021a).

The impacts of global warming are especially perceptible in the rise of extreme weather and climate events. Heatwaves

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are becoming more frequent and severe in almost every region, some regions face increased droughts (IPCC, 2021a) and/or increased flooding risks due to more intense rainfall (Park et al., 2020; Zhang et al., 2022a). These extremes have caused considerable damage to societies and ecosystems (Leach et al., 2020; Seneviratne et al., 2021).

The 2015 Paris Agreement marked a milestone in global climate action, aiming to limit global temperature rise to “well below 2 °C above pre-industrial levels” and pursuing efforts to cap it at 1.5 °C (UNFCCC, 2015). This goal reflects the understanding that even a “small” increase of 0.5 °C can dramatically amplify risks to socioeconomic systems and ecosystems (Schleussner et al., 2016; Rogelj et al., 2018). However, under current policies and emission trajectories, we are likely to reach 2 °C of warming by mid-century and around 3 °C by the end of the century (UNEP, 2024). The IPCC Sixth Assessment Report (AR6) employs new Shared Socioeconomic Pathways (SSPs), including a very high emission scenario (SSP5-8.5), that projects a potential global temperature increase of up to 4.4 °C above pre-industrial levels by 2100 (IPCC, 2021b). Consequently, assessing climate changes and extremes across various Global Warming Levels (GWLs)—ranging from 1.5 °C to 4 °C above pre-industrial—can clarify the impacts of global warming and provide a basis for developing adaptation strategies at different spatial and temporal scales (Xu et al., 2017; Lenton et al., 2019).

Vietnam is among the most climate-vulnerable countries, ranking sixth out of 84 developing nations (Eckstein et al., 2021). Its geographical location and socio-economic factors expose the country to significant climate risks. With a 3,260 km coastline and deltas covering 12% of the land area but housing 35% of the population, the country faces severe threats from sea-level rise and saltwater intrusion (Tran et al., 2017; Eslami et al., 2021). Sea levels in Vietnam have risen by 3–4 mm per year over the past 50 years, totaling 15–20 cm (Dong et al., 2019). This increasing trend will continue in future decades in all climate scenarios, threatening low-lying coastal areas. IPCC (2021b) global mean sea level projections for the end of the century range between 30 cm and 1 m relative to 1995–2014, but higher values cannot be excluded given the high uncertainties on the future evolution of polar ice sheets. Rising sea levels will increase the frequency and severity of flooding, particularly in low-lying coastal areas where a large portion of the Vietnamese population resides (Bangalore et al., 2019; Pham et al., 2023). Large regions such as the Mekong Delta, where land subsidence exacerbates relative sea level rise (Minderhoud et al., 2020), could fall below sea level. Vietnam’s economy is highly vulnerable to climate change, with over 60% of the workforce employed in weather-dependent sectors such as agriculture, construction, and manufacturing (GSO Vietnam, 2021). Agriculture, particularly rice cultivation—a staple food and major export commodity—faces significant risks. Temperatures exceeding 35 °C during the flowering stage could reduce yields by up to 10% (Tho & Umetsu, 2022). The fisheries sector, valued at approximately $2.3 billion, is also at considerable risk. A 2 °C rise in global temperature could shrink the area for pangasius farming in the Mekong Delta by up to 50% (FAO, 2022). Vietnam has experienced not only a significant temperature increase over the past decades—led to increased extreme temperatures and heatwaves (Woillez, 2024)—but also an increase in extreme rainfall events. From 1971 to 2010, the frequency and intensity of heavy rainfall events rose sharply, particularly in the northern and central regions of Vietnam (Nguyen et al., 2017). Heavy rainfall contributes to the increased risk of flooding and landslides and has severe impacts on agriculture, infrastructure, and local communities.

Climate projections are essential for understanding future environmental challenges, particularly in vulnerable regions like Vietnam. These projections provide information on future temperature, precipitation, and sea-level rise scenarios, enabling strategic planning for adapting to climate impacts across key sectors such as agriculture, water resources, and coastal protection. To date, the Ministry of Agriculture and Environment (formerly the Ministry of Natural Resources and Environment, MONRE) has published several national reports on climate change and sea level rise in Vietnam, continually refining its methodological approaches in line with IPCC guidance and development of climate models by the scientific community (MONRE 2009; 2012; 2016; 2021). Initially using the Special Report on Emission Scenarios (SRES) in the early reports (MONRE 2009; 2012), MONRE later transitioned to Representative Concentration Pathways (RCPs) in its subsequent publications (MONRE 2016; 2021). It is important to note that the MONRE reports employed the dynamical downscaling approach to generate future climate projections for Vietnam. While dynamic downscaling provides a better representation of local-scale feedback and processes and can maintain certain physical relationships among various climate variables (Seaby et al., 2013; Tangang et al., 2020), it remains highly computationally demanding. As a result, there were only a limited number of model experiments used in the latest report from MONRE (2021), i.e. 14 for temperatures and 7 for rainfall, which restricts the range of possible future climate scenarios investigated.

Recognizing these constraints, the Climate work package (WP1) of the GEMMES Vietnam project Phase 1 aimed to provide a more detailed and reliable picture of future climate scenarios by employing high-resolution, multi-model, and multi-scenario data (Espagne et al., 2021; Tran-Anh et al., 2023). By statistically downscaling the latest global climate models participating in the Coupled Model Intercomparison Project phase 6 (CMIP6) and incorporating a broader set of global greenhouse gas emissions scenarios, a high-resolution (10 km) climate dataset for Vietnam, known as CMIP6-VN, has been developed and made available (Tran-Anh et al., 2023). It is worth noting that in the context of rapid climate change, where even small increases in global temperature can lead to significant consequences—particularly in extreme events (IPCC, 2021b) — analyzing changes in climatological and extreme conditions across various GWLs is crucial. Accordingly, this study focuses on Vietnam, examining changes across GWLs from 1.5 °C to 4 °C. Using the CMIP6-VN dataset, we provide a detailed evaluation of projected changes in temperature and rainfall extremes. The results of this study are expected to offer a solid foundation for understanding future climate risks and guiding appropriate adaptation and mitigation strategies.

2 Data and method

2.1 Study area

Located in Southeast Asia, on the eastern side of the Indochina Peninsula with a coastline approximately 3,260 km long, Vietnam is one of the countries most severely affected by climate change (MONRE, 2016). The country stretches over 1,650 km from north to south for its continental part, with diverse landscapes ranging from mountainous regions in the northwest and central highlands to low-lying coastlands along the eastern shore. Its climate varies from a subtropical climate in the north to a tropical climate in the south. Following the climate classification of Nguyen & Nguyen (2004), based on specific criteria for radiation, temperature, and precipitation, our study distinguishes seven climatic subregions: Northwest (R1), Northeast (R2), Red River Delta (R3), North Central (R4), Central South (R5), Central Highlands (R6), and Southern (R7) (Fig. 1). In this study, we focus only on the continental part of Vietnam, and we do not consider the islands in the East Sea.

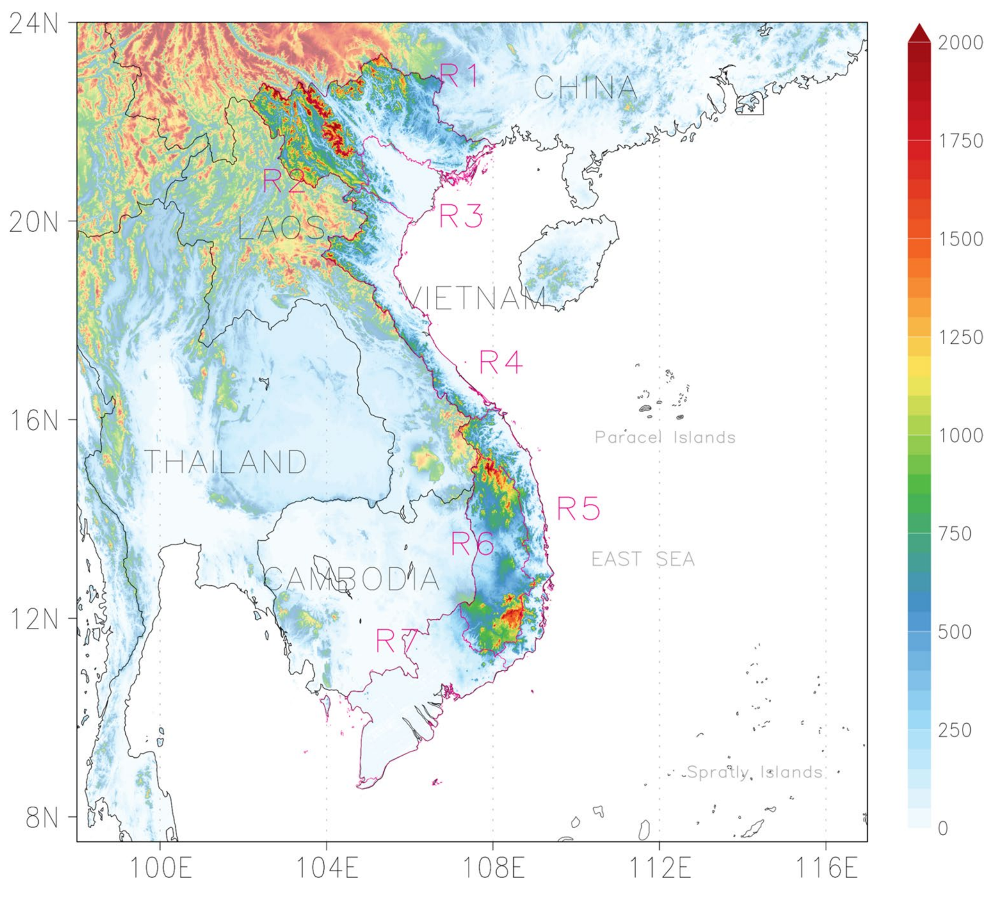

Fig. 1 Locations of the seven climatic sub-regions in Vietnam overlaid on the topographic map (meters above sea level) (Linke et al., 2019)

2.2 Models and scenarios

In the 6th IPCC Assessment Report (IPCC, 2021b) a new core set of 5 scenarios were used to investigate potential future climate evolutions with the latest generation of global climate models (CMIP6). These scenarios, starting in 2015, are internally consistent projections of greenhouse gases, aerosols, ozone-depleting substances, and land use based on assumptions of the evolutions of the socio-economic systems. They are labeled SSPx-y, where “SSPx” refers to a Shared Socio-economic Pathway (Riahi et al., 2017) and “y” to the approximate level of radiative forcing (in W/m^2) reached with this scenario in 2100:

- SSP1-1.9: A very low emission scenario aimed at controlling global temperature rise to 1.5 °C above pre-industrial level;
- SSP1-2.6: A low emission scenario focused on sustainable development, limiting the temperature rise to below 2 °C;
- SSP2-4.5: A medium emission scenario with partial mitigation efforts leading to a best estimate of a 2.7 °C global temperature rise by the end of the century (2081–2100);
- SSP3-7.0: A high emission scenario with limited climate policies where global temperature would rise by ~3.6 °C by the end of the century;
- SSP5-8.5: A very high emission scenario based on fossil fuel development, which would lead to a catastrophic warming of ~4.4 °C by the end of the century.

It has to be noticed that, for the first time in an IPCC report, global surface temperature changes relative to 1850–1900 for each scenario (Fig. 2) are not based solely on projections from the CMIP6 climate models, but also take into account observational constraints based on past simulated warming and an updated assessment of equilibrium climate sensitivity (ECS).

This study employs the CMIP6-VN dataset, a high-resolution climate projection dataset specifically developed for Vietnam (Tran-Anh et al., 2023). The dataset was constructed by statistically downscaling CMIP6 GCMs to a 10 km resolution using the Bias Correction and Spatial Disaggregation (BCSD) method. The performance of the CMIP6-VN dataset in reproducing Vietnam’s contemporary climate conditions during the reference period 1995–2014 has been systematically evaluated, and the validation results are presented in Appendix A. To ensure consistency within the GWL framework and to avoid potential bias from models exhibiting anomalously strong regional warming responses, a subset of 33 CMIP6 models was selected from the intersection of the CMIP6-VN dataset and the GWL threshold dataset (Hauser et al., 2022). Models with unusually high climate sensitivity and non-linear scaling of regional temperature responses across GWLs were excluded from the analysis. Details of the 33 CMIP6 GCMs and the associated scenarios used in the BCSD downscaling are provided in Table 1.

The multi-scenario analysis allows for the quantitative assessment of the relationship between global emission reduction efforts and the development of extreme rainfall and temperature events in Vietnam. The selected SSP scenario range not only provides a scientific basis for policy planning but also helps identify the unavoidable impacts even under maximum emission reduction conditions (SSP1-1.9), thereby guiding appropriate adaptation solutions. At the same time, comparing with high emission scenarios (SSP3-7.0, SSP5-8.5) highlights the potential risks when emissions are not controlled, reinforcing the urgency of Vietnam’s commitment to “Net Zero Emissions” (UNFCCC, 2022).

The CMIP6-VN dataset can be downloaded from: https://doi.org/10.6084/m9.figshare.c.6164352.

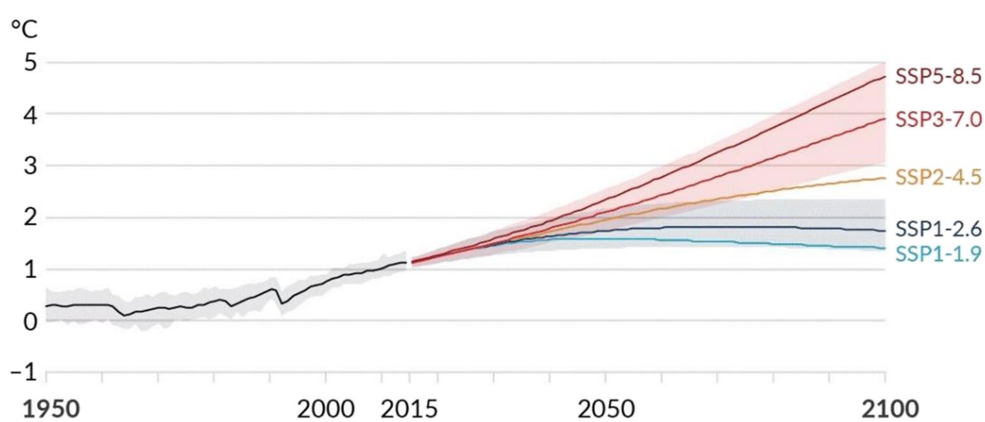

Fig. 2 Global surface temperature changes in °C relative to 1850–1900 for the historical period and the SSP scenarios (IPCC, 2021a). These changes were obtained by combining CMIP6 model simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity. The very likely uncertainty ranges for SSP1-2.6 and SSP3-7.0 are shown as shaded regions

Table 1 List of the 33 statistically downscaled CMIP6 GCMs (CMIP6-VN database, Tran-Anh et al. (2023)) and available periods and scenarios selected for this study. The column "country" indicates where the models are developed

N°	CMIP6 Model	Country	Horizontal Resolution (lat. x lon. in degree)	Historical period	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
				1995–2014	2015–2099				
1	ACCESS-CM2	Australia	1.88°x1.25°	t	-	t	t	t	t
2	ACCESS-ESM1-5	Australia	1.88°x1.25°	x	-	x	x	x	x
3	AWI-CM-1-1-MR	Germany	0.93°x0.94°	x	-	x	x	x	x
4	BCC-CSM2-MR	China	1.13°x1.13°	x	-	x	x	x	x
5	CAMS-CSM1-0	China	1.13°x1.12°	p	-	-	-	-	-
6	CESM2	USA	1.41°x1.42°	p	-	p	p	p	p
7	CESM2-WACCM	USA	1.25°x0.94°	p	-	p	-	p	p
8	CIESM	China	1.25°x0.94°	t	-	t	t	-	t
9	CMCC-ESM2	Italia	1.25°x1.25°	x	-	x	x	x	x
10	CNRM-CM6-1-HR	France	1.25°x0.94°	x	-	x	x	x	x
11	CNRM-ESM2-1	France	0.5°x0.5°	x	x	x	x	x	x
12	CanESM5	Canada	1.41°x1.39°	x	x	x	x	x	x
13	EC-Earth3	Europe	0.7°x0.7°	x	-	x	x	x	x
14	EC-Earth3-Veg	Europe	0.7°x0.7°	x	x	x	x	x	x
15	FGOALS-f3-L	China	1.25°x0.8°	p	-	p	-	p	p
16	FGOALS-g3	China	2°x2.03°	x	x	x	x	x	x
17	FIO-ESM-2-0	China	1.25°x1.25°	x	-	p	-	-	p
18	GFDL-ESM4	USA	1°x1°	x	x	x	x	x	x
19	GISS-E2-1-G	USA	2.5°x2.5°	x	x	x	x	x	x
20	HadGEM3-GC31-LL	UK	1.88°x1.88°	x	-	x	x	-	x
21	HadGEM3-GC31-MM	UK	0.83°x0.56°	x	-	x	-	-	x
22	IITM-ESM	India	1.88°x1.89°	p	-	p	-	p	p
23	INM-CM5-0	Russia	2°x1.5°	x	-	x	x	x	x
24	IPSL-CM6A-LR	France	2.5°x1.27°	x	x	x	x	x	x
25	KACE-1-0-G	Korea	1.88°x1.88°	p	-	p		p	p
26	MCM-UA-1-0	USA	3.75°x2.24°	p	-	p		p	p
27	MIROC-ES2L	Japan	1.41°x1.41°	x	x	x	x	x	x
28	MIROC6	Japan	2.81°x2.77°	x	x	x	x	x	x
29	MPI-ESM1-2-HR	Germany	0.94°x0.94°	x	-	x	x	-	x
30	MRI-ESM2-0	Japan	1.13°x1.13°	x	x	x	x	x	x
31	NESM3	China	1.88°x1.88°	x	-	x	x	-	x
32	NorESM2-MM	Norway	1.25°x0.94°	p	-	p	p	p	p
33	TaiESM1	Taiwan	1.25°x0.94°	p	-	-	-	p	p

x: available for both precipitation and temperature

t: only temperature

p: only precipitation

2.3 The GWL thresholds

The determination of the time when GWLs are reached by the CMIP6 models under the different SSP scenarios is based on the results of Hauser et al. (2022). A GWL is defined as the point at which the global mean surface temperature (GMST) exceeds a certain threshold compared to the pre-industrial period (1850–1900). GMST is determined by averaging surface air temperatures over both land and ocean. To minimize short-term variability, a 21-year window is employed, encompassing the initial year (Y_{GWL}) when the 21-year centered average of the GMST anomaly series first exceeds the threshold and 10 years preceding and following that year. Note that this 21-year window, chosen for better symmetry regarding Y_{GWL}, differs slightly from Hauser et al. (2022), who applied a 20-year window with 10 years preceding and 9 years following Y_{GWL}. 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.

Figure 3 shows the projected timing when GMST anomalies relative to the pre-industrial period (1850–1900) exceed 1.5 °C, 2 °C, 3 °C, and 4 °C under various SSP scenarios, specifically for the CMIP6 models used for CMIP6-VN (Table 1). A significant inter-model spread is observed in the timing of when a GWL is reached for a given SSP scenario. For the 1.5 °C threshold, aligned with the Paris Agreement's mitigation goals (UNFCCC, 2015), all models project exceedance under SSP1-2.6 to SSP5-8.5. Even under the ambitious SSP1-1.9 scenario, designed to limit warming to 1.5 °C (IPCC, 2018), 7 out of 10 models exhibit exceedance, with the multi-model ensemble (MME) indicating a

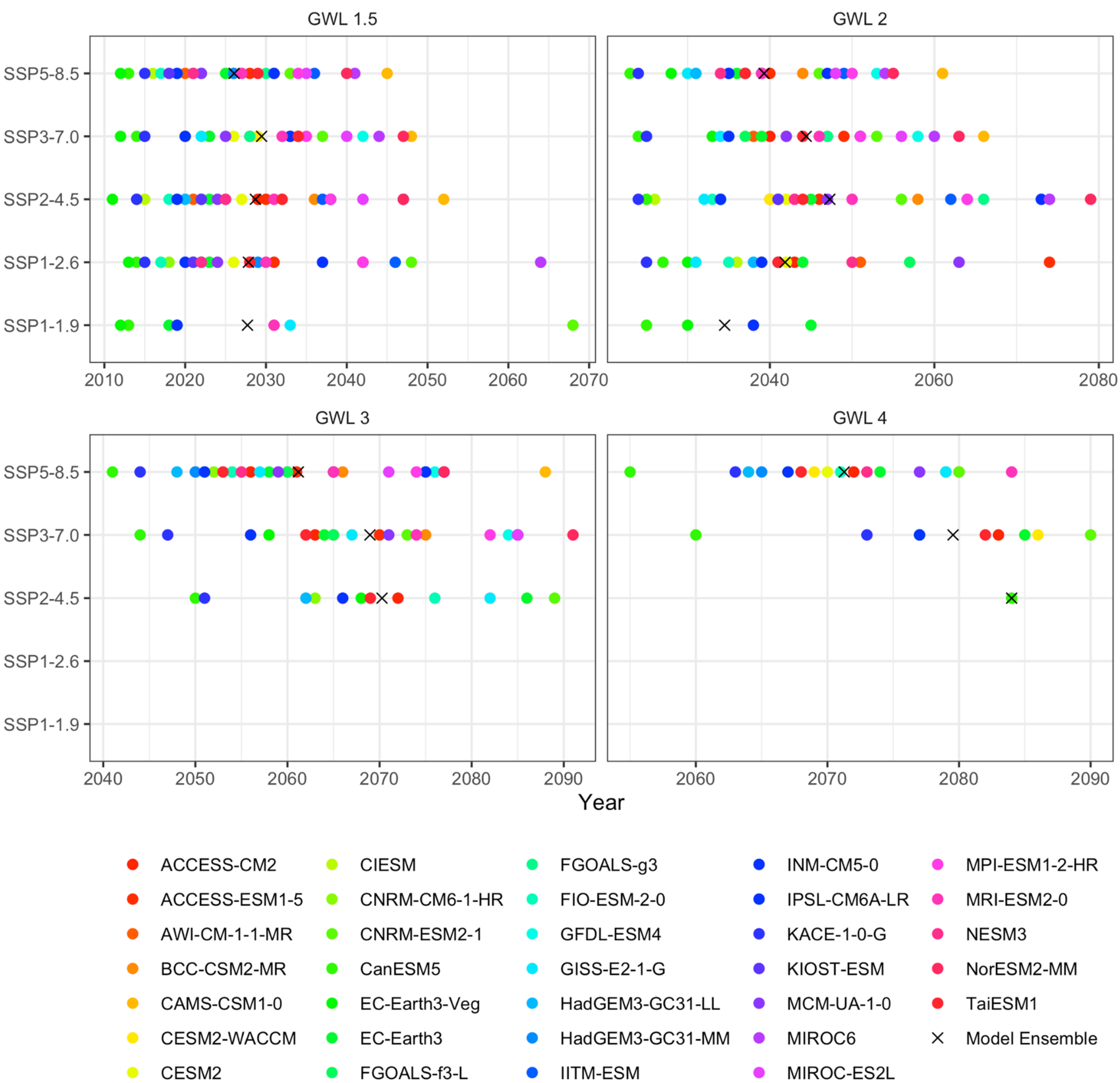

Fig. 3 Projected years when GMST crosses 1.5 °C, 2 °C, 3 °C, and 4 °C thresholds for each of the 33 CMIP6 models under scenarios SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Black crosses represent the MME crossing times for each threshold

crossing by 2027. This highlights the very high challenges of achieving the 1.5 °C target despite rigorous mitigation efforts hypothesized in this scenario. With 2024 now officially the warmest year on record, at 1.55 °C above pre-industrial level, the long-term goal of the Paris Agreement appears "in grave danger". Under SSP1-2.6 to SSP2-4.5, MME crossing years for the 1.5 °C threshold range from 2025 (SSP5-8.5) to 2029 (SSP3-7.0). The 2 °C threshold is exceeded in all scenarios, including by 4 of 10 models under SSP1-1.9. MME crossing years range from 2039 (SSP5-8.5) to 2048 (SSP2-4.5), showing substantial risks and impacts even at this "safer" 2 °C threshold. The SSP1-2.6 scenario may limit global warming below 3 °C by the end of the 21 st century. However, under SSP2-4.5, 12 of 22 models exceed this threshold around 2071 (MME). Higher emission scenarios (SSP3-7.0 and SSP5-8.5) project 3 °C exceedance by 2068 and 2062, respectively, a level linked to severe impacts (IPCC, 2014). The catastrophic 4 °C threshold is reached under SSP3-7.0 and SSP5-8.5, with MME crossing years around 2079 and 2073, respectively. Notably, 8 of 18 models under SSP3-7.0 and 16 of 23 under SSP5-8.5 exceed this threshold, emphasizing the severe risks of unabated emissions.

However, while CMIP6 climate models include a new and improved representation of processes and a higher spatial resolution than the previous generation (CMIP5), they also show a broader range of climate sensitivity, as illustrated in Fig. 3. A subset of models have an ECS above the "likely" or even the "very likely" range assessed in IPCC AR6 based on multiple lines of evidence. These "hot" models simulate a warming rate higher than previously expected for a given scenario, which does not seem consistent with other lines of evidence. Therefore, using the ensemble mean of GCM projections for regional climate impact assessment, as used to be done in previous IPCC reports and many other studies, may lead to an overestimation of the magnitude of change. To overcome this issue, in this study, we follow the IPCC AR6 approach and the recommendations of Hausfather et al. (2022), basing our analysis on global warming levels (GWLs) rather than on specific time periods. This approach is justified by the fact that for many climate variables, such as temperature and precipitation, the patterns of future changes are strongly related to GWL but more or less independent of the pathway or the time at which the GWL is reached (IPCC, 2021b). The period during which a given GWL may be reached in the future depending on the climate scenario can be deduced from the IPCC projections provided in Fig. 2. Nevertheless, as a high climate sensitivity cannot be completely ruled out, the "hot" models remain useful to investigate tail risks and to offer insights into worst-case scenarios that, although considered unlikely, could lead to significant consequences.

2.4 Climate extreme indices

This study uses standardized indices from the Expert Team on Climate Change Detection and Indices (ETCCDI, https://www.wcrp-climate.org/etccdi), approved by the World Meteorological Organization (WMO), to assess climate extremes in Vietnam under different GWLs. The temperature-related indices are categorized into four groups: intensity (TXx for maximum daily temperature); frequency (TX90p and TN10p for days and nights exceeding the 90th and 10th percentiles of the 1995–2014 baseline); hot day thresholds (SU35, SU37 for days exceeding specific temperatures); and heatwave/cold spell metrics (WSDI, CSDI, HWD, HWI for duration and intensity of extreme events). Precipitation-related indices (Rx1day, Rx5day, R50mm, R100mm, CDD, CWD) are also included to provide a comprehensive analysis of climate extremes in Vietnam. Details and definitions of the extreme climate indices used in this study are provided in Table 2. Drought events are investigated in another study (Nguyen-Xuan et al., 2025).

Extreme climate indices are analyzed for each GWL across all CMIP6-VN models. To estimate changes in extreme events, the indices listed in Table 2 are calculated as 21-year averages for each GWL and compared to the 1995–2014 baseline.

2.5 Signal-to-noise ratio

To assess the robustness of the projected changes, we use the signal-to-noise ratio (SNR) method as proposed by Li and Zhou (2010). In this method, SNR evaluates the strength of the multi-model ensemble mean signal relative to inter-model variability and is defined as:

$$SNR = \frac{Signal}{Noise} \quad (1)$$

In our analysis, each scenario is considered equally likely, and within each scenario, all climate models are assigned equal weight or probability. 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

Table 2 Details of extreme temperature- and rainfall-related indices used in this study

No.	Acronym	Name	Units	Definition	Index Type
Temperature extremes					
1	TXx	Hottest day	°C	Annual maximum value of daily maximum temperature (TX)	Intensity
2	TNn	Coldest night	°C	Annual minimum value of daily minimum temperature (TN)	Intensity
3	TX90p	Warm days	%	Annual percentage of days when the daily maximum temperature exceeds the calendar-day 90th percentile, based on a 5-day running window from the 1995–2014 baseline period	Threshold-based
4	TN10p	Cool nights	%	Annual percentage of days when the daily minimum temperature (TN) falls below the calendar-day 10th percentile, based on a 5-day running window from the 1995–2014 baseline period	Threshold-based
5	SU35	Summer days, also called hot days (≥35 °C)	Days	Annual number of days when the daily maximum temperature (TX)≥35, a commonly used heat threshold in Vietnam (Ngo & Bui, 2023; Thanh et al., 2021)	Frequency
6	SU37	very hot days (≥37 °C)	Days	Annual number of days when the daily maximum temperature (TX)≥37 °C, a threshold representing severe heat conditions in Vietnam (Ngo & Bui, 2023; Thanh et al., 2021)	Frequency
7	HWD	Heatwave duration	Days	Annual number of days with at least 3 consecutive days hotter than the 90th percentile of the reference period	Duration
8	HWI	Heatwave intensity	°C	Annual average of maximum daily temperature during the heatwave period	Intensity
Precipitation extremes					
9	Rx1day	Maximum 1-day precipitation	mm	Annual maximum precipitation in a single day	Intensity
10	Rx5day	Maximum 5-day precipitation	mm	Annual maximum accumulated precipitation over any 5 consecutive days	Intensity
11	R95pTOT	Very wet day precipitation	mm	Annual total precipitation from days with daily precipitation > 95th percentile	Intensity
12	R50mm	Heavy precipitation days (≥50 mm)	Days	Annual number of days with daily precipitation ≥ 50 mm, representing heavy rainfall events with potential flood impacts in Vietnam (Ngo-Duc, 2023; Chen et al., 2019)	Frequency
13	R100mm	Very heavy precipitation days (≥100 mm)	Days	Annual number of days with daily precipitation ≥ 100 mm, indicative of extreme rainfall events associated with flood risk in Vietnam (Ngo-Duc, 2023; Chen et al., 2019)	Frequency
14	CWD	Consecutive wet days	Days	Annual maximum number of consecutive days with daily precipitation ≥ 1 mm	Duration
15	CDD	Consecutive dry days	Days	Annual maximum number of consecutive days with daily precipitation < 1 mm	Duration
16	RI	Rainfall intensity	mm/day	Annual ratio of the total amount of rain (rainfall depth) falling during wet days (daily precipitation > 1 mm) to the duration of those wet days	Intensity

of each model and each scenario as a distinct pathway for future projections. 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:

$$Signal = MSMME = \left| \frac{1}{n} \left(\sum_{i=1}^{n} x_i \right) \right| \quad (2)$$

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:

$$Noise = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - MSMME)^2} \quad (3)$$

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).

3 Results and discussion

3.1 Temperature increase in Vietnam corresponding to GWLs of 1.5 °C, 2 °C, 3 °C and 4 °C

Figure 4 depicts the projected warming trends of average surface temperature in Vietnam for individual CMIP6-VN models and their MME under different SSPs. High-emission scenarios SSP5-8.5 and SSP3-7.0 exhibit substantially higher temperature increases compared to lower-emission scenarios SSP2-4.5, SSP1-2.6, and the sustainable pathway SSP1-1.9.

Compared to the baseline period 1995–2014, the MME projects an average surface temperature rise of over 3.83 °C for 2080–2099 under SSP5-8.5, while the increase is limited to 0.91 °C under SSP1-1.9. The MME results, based on 5-year moving averages, clearly illustrate the diverging temperature trajectories across scenarios and still show inherent fluctuations within each time step. The temperature increase in Vietnam relative to 1995–2014 projected by the CMIP6 models are 0.74 °C, 1.23 °C, 1.87 °C, and 2.24 °C for GWLs of 1.5 °C, 2 °C, 3 °C, and 4 °C above pre-industrial levels

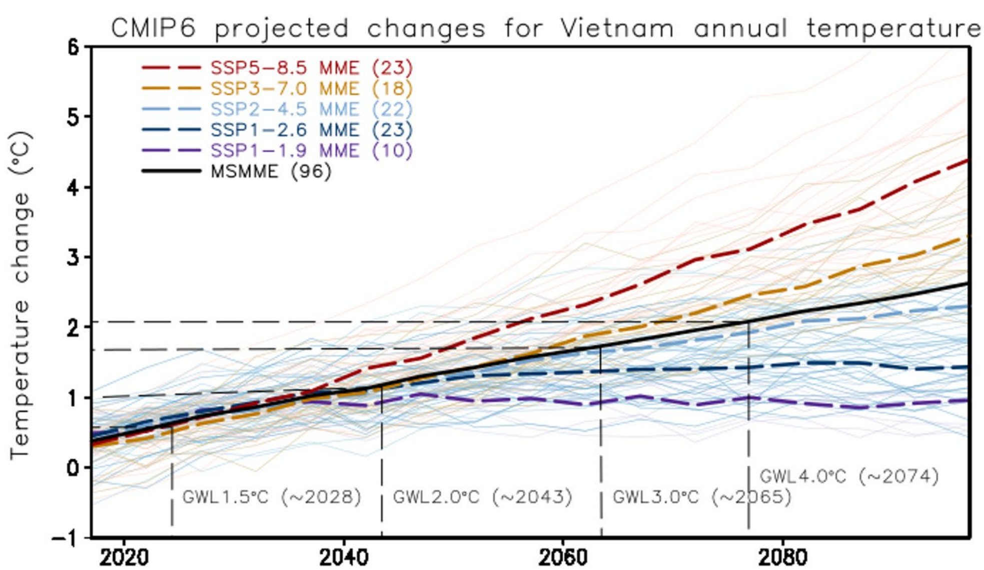

Fig. 4 Projected mean near-surface temperature changes in Vietnam relative to the 1995–2014 baseline under scenarios SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 for 2015–2099. Thin solid lines show individual model projections, bold dashed lines indicate the MME mean for each scenario for 5-year moving averages, and the thick black line represents the MSMME mean. The number of model simulations per scenario is given in brackets. Dashed black lines mark the timing when the MSMME global temperature crosses each GWL relative to pre-industrial levels, with corresponding Vietnam warming levels relative to the baseline, according to the MSMME of CMIP6 simulations

respectively. Note that these projections correspond to the MSMME of CMIP6 simulations and therefore include the models with a high climate sensitivity. As the result, the timings of crossing the different GWLs differ from the IPCC (2021b) assessment according to multiple lines of evidence (see Fig. 2).

3.2 Changes in temperature-related extremes

The analysis of temperature extremes across Vietnam reveals significant shifts as GWLs increase (Fig. 5). Even a "modest" increase in warming from 1.5 °C to 2 °C leads to clear changes in temperature extremes, with the hottest days projected to become substantially hotter. By mid-century, when the 2 °C GWL could be reached under current policies (UNEP, 2024), the likely range (interquartile range, 25th–75th percentile) of maximum temperature increase is projected to be 1.2–1.9 °C nationally. At 3 °C GWL, which could be reached by the end of the century under current policies, the likely range of maximum temperature is projected to increase significantly by 2.1–3.0 °C. Under the most severe scenario of 4 °C GWL, maximum temperatures are likely to rise by 3.1–4.1 °C.

Spatial variations are notably pronounced, with northern and southern regions experiencing different intensities of change. In the Red River Delta region (R3), the maximum temperature's likely range is expected to increase from 0.8 to 1.4 °C under 1.5 °C warming to 3.3–4.4 °C under 4 °C GWL. The northern regions, particularly under higher emission scenarios, show the most severe temperature intensification. The warming in North Vietnam (R1–R4) is approximately 0.6 °C higher at 1.5 °C GWL and up to 1 °C higher at 4 °C GWL compared to the South (R5–R7) (Fig. 6; Table 3), with the difference becoming more pronounced at higher GWLs. Similarly, the coldest night temperature TNn shows a spatial pattern broadly consistent with TXx but with a weaker magnitude (Fig. 7). The increase in TNn is highest in the northern regions, followed by the southern regions, while the coastal and central regions exhibit the smallest changes, indicating a clear north–south gradient with muted nighttime warming along the central coast. At the national scale, TNn is projected to rise from approximately 0.5–0.6 °C at 1.5 °C GWL to 2.5–3.4 °C at 4.0 °C GWL. These increases are consistently lower than those of TXx by about 0.5–1.7 °C across all warming levels, suggesting that extreme daytime temperatures intensify more rapidly than cold nighttime extremes.

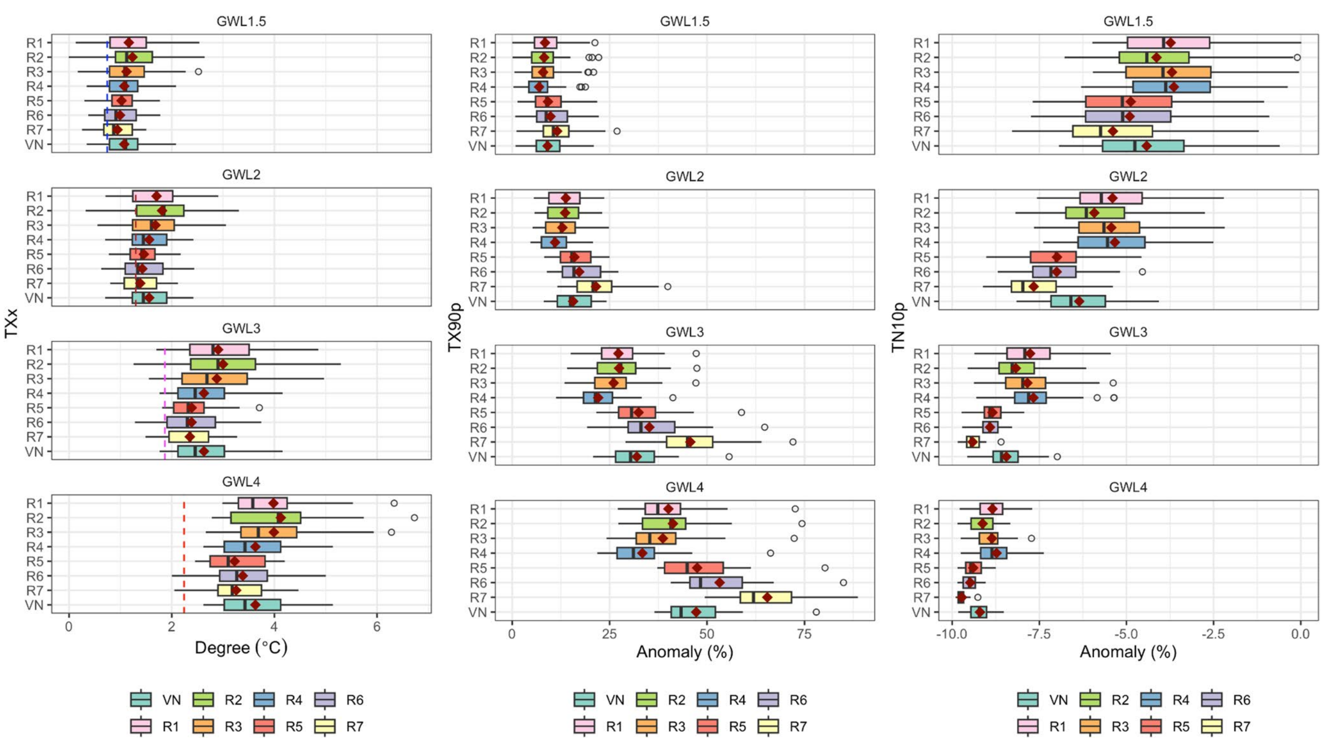

Fig. 5 Projected changes of TXx (left), TX90p (middle), and TN10p (right) over Vietnam and its seven sub-climatic regions, relative to the 1995–2014 baseline period, under GWLs 1.5 °C, 2 °C, 3 °C and 4 °C. Boxplots visualize the distribution of changes projected by the CMIP6-VN models, with boxes presenting the interquartile range (IQR), vertical bands showing the median, and whiskers extending to the most extreme data points within 1.5 times the IQR from the boxes. Any outlier models beyond 3 times the IQR are shown as individual white dots. The multi-model ensemble (MME) mean change is highlighted by red dots. For TXx plots, vertical dashed lines denote the warming levels over Vietnam relative to the baseline period, corresponding to GWLs of 1.5 °C (blue), 2 °C (brown), 3 °C (pink), and 4 °C (red)

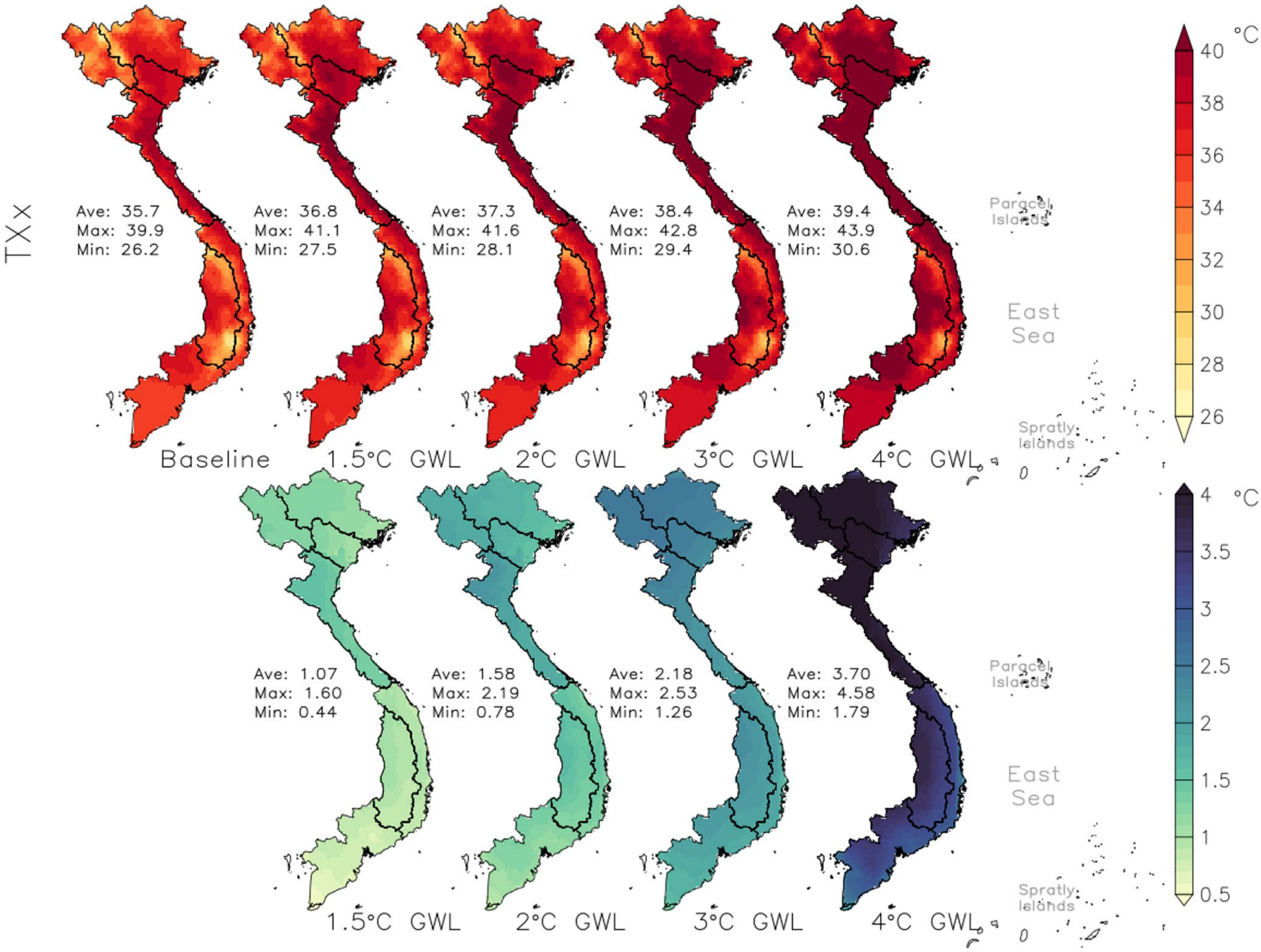

Fig. 6 Spatial patterns of projected changes in the 21-year mean of TXx over Vietnam under different GWLs by MSMME. The top panels show the absolute projected temperature at each GWL, and the bottom panels display the corresponding anomalies relative to the 1995–2014 baseline period. Hatched areas highlight regions where the SNR < 1, indicating low model agreements

Under a 2 °C GWL scenario, the national average for TX90p is projected to increase 2.5 times, reaching 25.5%. Larger increases are projected at higher GWLs: at 3 °C GWL, TX90p is expected to rise further to 42% and could increase to as much as 57.5% under a 4 °C GWL scenario. Warm days are expected to rise more rapidly in the southern regions (R6, R7), reaching 69.7% of the year on average, compared to 50% in the northern regions (R1–R3) (Fig. 8) at 4 °C GWL. Conversely, TN10p is projected to decrease significantly nationwide, dropping by 3.3%–5.1% under the 1.5 °C GWL and by 8.7%–9.7% under the 4 °C GWL, with a faster decline in the south (Fig. 9).

Although model confidence varies largely across different indices (Table 3), the SNR values suggest robust agreement on the increase in TXx and Tx90p, and decrease in TNn and TN10p across all GWLs (Fig. 6, 7, 8 and 9).

Figure 9 highlights a sharp increase in SU35 as GWLs intensify. From a baseline of 12.3 days annually, the national average of SU35 more than doubles to 25.1 days at 1.5 °C GWL. This upward trend intensifies substantially at each threshold, reaching 33.9 days at 2 °C GWL, 56.6 days at 3 °C GWL, and 90.4 days at 4 °C GWL - representing a 6.2-fold increase from the baseline period. The southern region (R7) is most affected at a 4 °C GWL, experiencing an average of 141 days above 35 °C annually. Some local areas may face 200–221 days of extreme heat, covering approximately two-thirds of the year and indicating nearly year-round hot conditions. Similarly, SU37 (see Appendix B, Figure B1) rises to an annual average of 38.1 days at the 4 °C GWL, a fivefold increase from the 1.5 °C threshold. Although a significant increase in SU35 is projected for most regions, the high uncertainty ranges in the model projections compared

Table 3 Projected changes in temperature-related extreme indices in Vietnam and in the seven sub-climatic regions under different GWLs relative to the baseline period 1995–2014

Scenario	Region	TXx	TNn	TX90p	TN10p	SU35	SU37	HWD	HWI
	Unit*	°C	°C	%	%	Days	Days	Days	°C
GWL1.5	VN	36.8 (+1±1.4)	10.7 (+0.5±0.7)	18.9 (+9.1±4.8)	5.7 (−4.1±3)	25.2 (+12.6±19.4)	7.9 (+5.8±14.5)	11.2 (+5.8±7.1)	34.8 (+0.4±0.8)
	R1	36.7 (+1.2±1.8)	5.1 (+0.5±0.9)	18.2 (+8.4±4.6)	6.4 (−3.4±3)	16.9 (+10.3±16.1)	5.3 (+4.5±12.5)	9.6 (+5.3±5.8)	34.2 (+0.5±1)
	R2	35.1 (+1.2±1.6)	4.5 (+0.5±0.9)	18 (+8.1±4.6)	6.1 (−3.7±4)	8.4 (+6.9±19.5)	3.9 (+3.7±13.5)	10.1 (+5.6±8.3)	32.6 (+0.5±1)
	R3	38.5 (+1.1±1.8)	7 (+0.5±0.9)	17.7 (+7.9±4.5)	6.5 (−3.4±2.9)	29.7 (+14.1±17.6)	9.9 (+6.9±15)	9.5 (+5±5.7)	35.7 (+0.4±1)
	R4	40.1 (+2.1±1.4)	8 (+0.5±0.8)	16.7 (+6.9±3.8)	6.5 (−3.4±2.6)	41.9 (+16.3±19.4)	17.2 (+10.3±14.5)	10.7 (+5.6±7.1)	37.5 (+1.4±0.8)
	R5	36.9 (+0.9±1.2)	14.6 (+0.5±0.5)	19 (+9.2±4.7)	5.2 (−4.6±2.8)	30 (+15.3±22.6)	8.6 (+6.8±17.9)	12.5 (+6.9±7.6)	35.1 (+0.4±0.7)
	R6	35.7 (+0.9±1.3)	12.3 (+0.5±0.6)	19.8 (+9.9±5.3)	5.2 (−4.6±2.9)	21.1 (+11.5±23.1)	6.9 (+5.7±16.5)	12.7 (+6.5±9.4)	34 (+0.4±0.8)
	R7	36.6 (+0.7±0.9)	19.3 (+0.6±0.5)	21.5 (+11.6±5.8)	4.8 (−5.1±3)	28.5 (+14.9±18.7)	5.1 (+4.2±11.6)	13 (+6.3±6.5)	35.3 (+0.3±0.5)
GWL2	VN	37.3 (+1.5±1.5)	11.2 (+1±0.6)	25.5 (+15.7±5.3)	3.5 (−6.4±1.1)	33.9 (+21.4±26.6)	10.9 (+8.8±19)	15.5 (+10.1±10)	34.9 (+0.5±0.8)
	R1	37.2 (+1.7±1.7)	5.6 (+1±0.8)	23.6 (+13.8±5.1)	4.4 (−5.4±1.3)	23.8 (+17.3±20.4)	7.3 (+6.5±14.9)	13.4 (+9.2±7.7)	34.3 (+0.6±0.9)
	R2	35.7 (+1.9±1.9)	5 (+1±0.8)	23.3 (+13.5±4.8)	3.9 (−5.9±1.3)	12 (+10.5±28)	5.4 (+5.2±18.6)	14 (+9.5±12.5)	32.7 (+0.6±0.9)
	R3	39 (+1.7±1.7)	7.6 (+1.1±0.8)	22.7 (+12.9±4.9)	4.4 (−5.4±1.3)	39.3 (+23.8±23.1)	13.6 (+10.6±18.1)	13 (+8.4±7.7)	35.8 (+0.5±0.9)
	R4	40.6 (+2.6±1.5)	8.5 (+1±0.7)	20.8 (+11±4.1)	4.5 (−5.3±1.3)	51.4 (+25.7±26.6)	22.5 (+15.6±19)	13.6 (+8.5±10)	37.6 (+1.5±0.8)
	R5	37.3 (+1.4±1.4)	15.1 (+0.9±0.5)	25.8 (+16±5)	2.9 (−7±1)	40.7 (+25.9±33.2)	12.5 (+10.7±25.6)	17.6 (+12±11.1)	35.2 (+0.5±0.7)
	R6	36.2 (+1.4±1.6)	12.8 (+1±0.5)	27.2 (+17.3±5.9)	2.9 (−7±1)	28.6 (+19±33.9)	9.9 (+8.7±23.5)	17.5 (+11.3±14)	34.1 (+0.5±0.8)
	R7	37.1 (+1.2±0.9)	19.7 (+1±0.5)	31.5 (+21.6±6.6)	2.2 (−7.7±1)	41 (+27.5±24.2)	7.6 (+6.7±13.5)	18.6 (+11.9±8.7)	35.4 (+0.4±0.5)
GWL3	VN	38.4 (+2.2±1.4)	12.2 (+2±0.7)	42 (+32.2±7.9)	1.4 (−8.4±0.6)	56.6 (+44±25.9)	19.7 (+17.6±18.6)	26.2 (+20.8±9.6)	35.2 (+0.9±0.7)
	R1	38.4 (+2.5±1.6)	6.7 (+2.2±0.9)	37.3 (+27.4±7.2)	2.1 (−7.8±0.9)	43.2 (+36.6±20.4)	14.8 (+13.9±14.8)	22.8 (+18.6±7.4)	34.7 (+1±0.8)
	R2	36.9 (+2.5±1.8)	6.1 (+2.1±0.8)	37.2 (+27.3±7)	1.6 (−8.2±0.8)	19.6 (+18±24.8)	7.4 (+7.2±15.5)	23.6 (+19±11.5)	33 (+0.9±0.8)
	R3	40.2 (+2.4±1.6)	8.6 (+2.1±0.8)	36 (+26.2±7.2)	2 (−7.8±0.9)	64.4 (+48.8±23.2)	26.1 (+23.1±18.8)	22 (+17.4±7.6)	36.2 (+0.8±0.8)
	R4	41.7 (+3.3±1.4)	9.5 (+1.9±0.8)	32 (+22.2±6.3)	2.2 (−7.7±0.9)	73.6 (+47.9±25.9)	36.2 (+29.3±18.6)	20.7 (+15.6±9.6)	37.9 (+1.9±0.7)
	R5	38.3 (+2±1.3)	15.9 (+1.8±0.5)	42.5 (+32.7±7.6)	1 (−8.8±0.4)	65.2 (+50.4±31.4)	21.8 (+19.9±25.7)	29.2 (+23.6±10.2)	35.5 (+0.8±0.7)
	R6	37.2 (+2.1±1.6)	13.7 (+2±0.5)	45.3 (+35.5±9.2)	0.9 (−8.9±0.4)	45.1 (+35.5±31.2)	16.2 (+15.1±21.4)	28 (+21.8±12.7)	34.5 (+0.9±0.7)
	R7	38.1 (+1.9±0.9)	20.7 (+2±0.6)	56 (+46.1±9.4)	0.5 (−9.4±0.3)	79.8 (+66±26.8)	18 (+17.1±15.1)	34.5 (+27.8±9.6)	35.7 (+0.7±0.5)
GWL4	VN	39.5 (+3.6±1.4)	13.3 (+3±1.1)	57.5 (+47.7±10.3)	0.6 (−9.2±0.4)	90.4 (+77.8±37.6)	38.2 (+36.1±30.1)	40.3 (+34.8±12.9)	35.7 (+1.3±0.7)
	R1	39.6 (+4±1.5)	8 (+3.3±1.2)	50.4 (+40.5±10.3)	1 (−8.8±0.5)	70.6 (+63.8±31.1)	31.2 (+30.3±26.7)	34.1 (+29.9±10.4)	35.3 (+1.5±0.7)
	R2	38.2 (+4.3±1.8)	7.5 (+3.4±1.2)	51 (+41.2±10.6)	0.7 (−9.1±0.4)	36.4 (+34.8±34.5)	15.1 (+14.9±22.2)	36 (+31.5±14.5)	33.5 (+1.3±0.8)
	R3	41.4 (+4±1.5)	9.8 (+3.2±1.2)	48.9 (+39.1±10.8)	1 (−8.9±0.5)	95.4 (+79.5±31.8)	47.8 (+44.8±31)	32.9 (+28.4±10.3)	36.6 (+1.3±0.7)

Table 3 (continued)

Scenario	Region	TXx	TNn	TX90p	TN10p	SU35	SU37	HWD	HWI
	R4	42.8 (+4.8±1.4)	10.6 (+2.9±1.1)	43.6 (+33.7±10)	1.1 (−8.7±0.6)	100.2 (+74.2±37.6)	56.9 (+49.9±30.1)	29.4 (+24.4±12.9)	38.4 (+2.3±0.7)
	R5	39.1 (+3.2±1.2)	16.7 (+2.5±0.9)	58.1 (+48.2±10.3)	0.5 (−9.4±0.3)	97.8 (+82.9±38.1)	39.4 (+37.5±34)	41.8 (+36.3±11.5)	35.9 (+1.2±0.6)
	R6	38.2 (+3.5±1.5)	14.7 (+2.9±0.9)	63.6 (+53.7±10.9)	0.4 (−9.5±0.3)	74.6 (+65.2±41.5)	31.4 (+30.3±29.7)	43.5 (+37.2±15.7)	34.9 (+1.3±0.7)
	R7	39 (+3.1±0.9)	21.6 (+2.9±1)	75.9 (+66±9.8)	0.2 (−9.7±0.2)	141 (+127.2±50.7)	45 (+44±36.9)	56.8 (+50.1±16)	36 (+1±0.4)

*The unit, for instance, °C (change in °C ± 1STD), represents the projected temperature value and its deviation from a baseline in °C, with ± 1STD indicating the standard deviation (model uncertainty). For example, 36.8 (+1 ± 1.4) means the projected temperature is 36.8 °C, with an increase of +1 °C and an uncertainty range of ± 1.4 °C

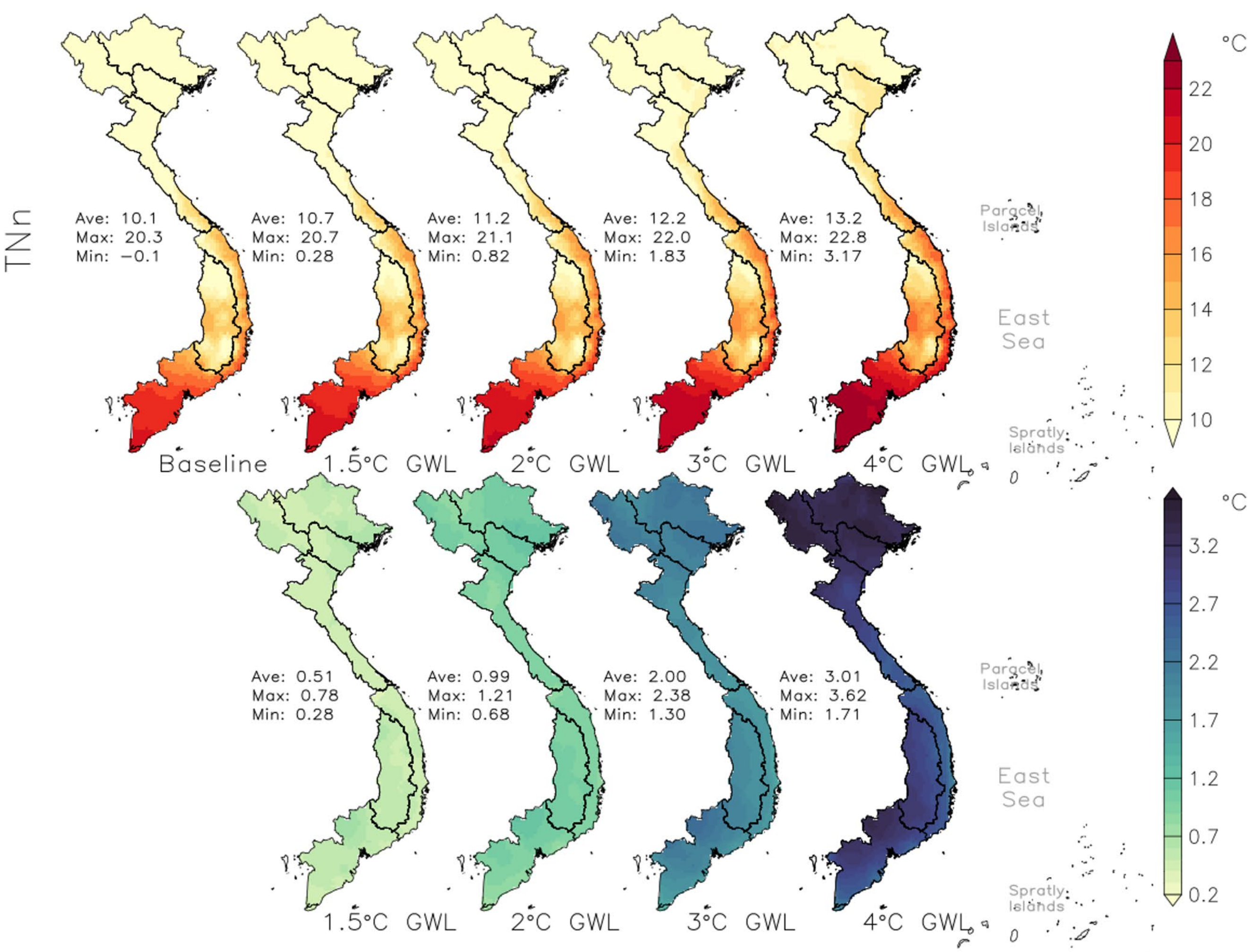

Fig. 7 Similar to Fig. 6 but for TNn

to the anomalies (Table 3) result in low SNR values for the R2 and R6 regions at lower GWLs. This indicates reduced confidence in the estimated magnitude of the projected changes in these areas.

As Vietnam faces hotter conditions across all GWLs, HWD is projected to increase significantly. At 2 °C GWL, the national average HWD increases from 5.4 days at baseline to 15.5 days. This trend continues with HWD reaching 26.2 days at 3 °C GWL and escalating to 40.2 days at the 4 °C threshold—representing 3.9 to 6.5 times the baseline (Fig. 11). However, this increasing trend shows considerable variability, with uncertainty often exceeding the anomalies

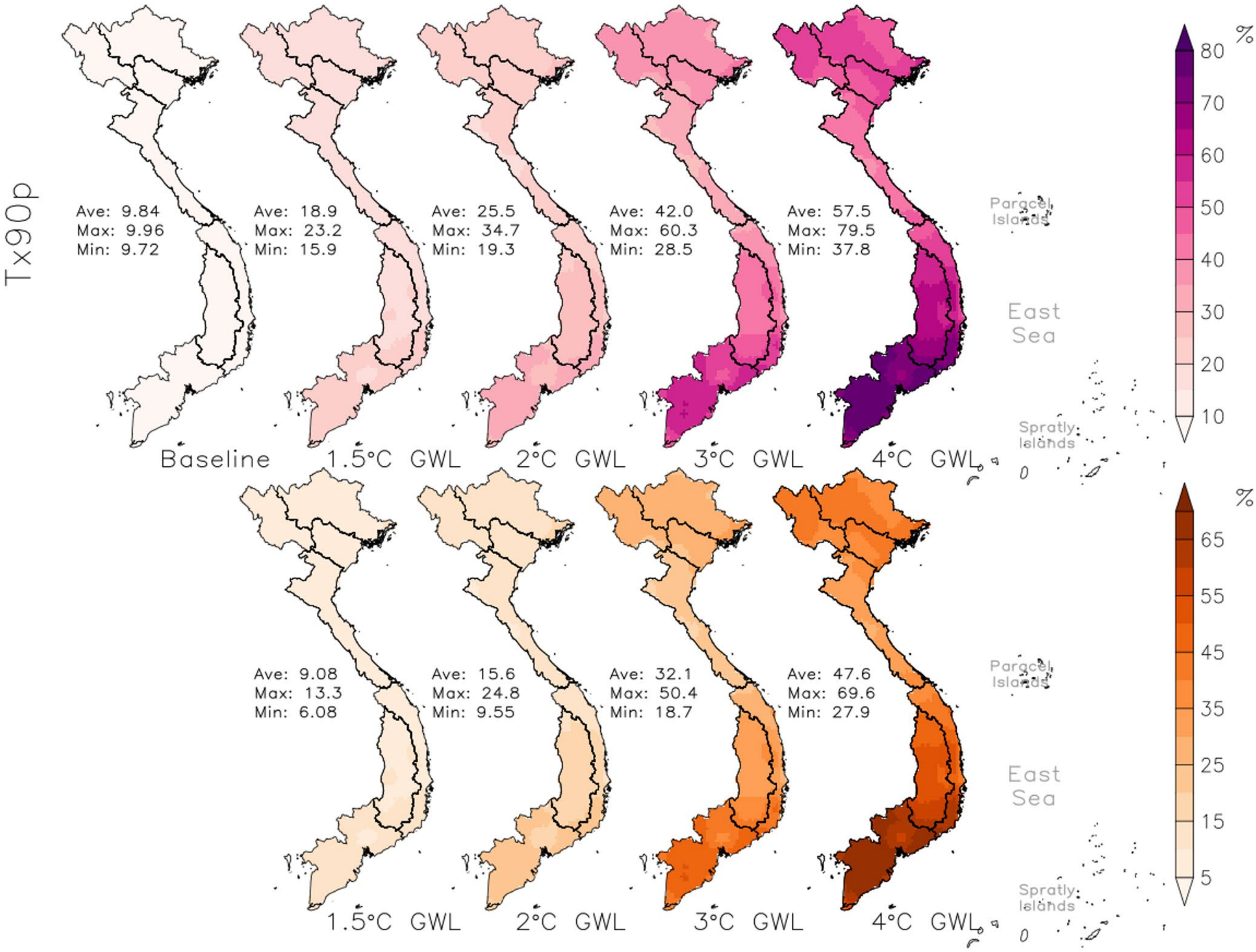

Fig. 8 Similar to Fig. 6 but for Tx90p

at the 1.5 °C and 2 °C thresholds (Table 3), highlighting substantial uncertainty in projections at the relatively lower GWLs. Model agreement is strengthened at higher GWLs, particularly at the 3 °C and 4 °C thresholds, suggesting greater confidence in the projected increases. On the other hand, HWI exhibits a more modest increase, from an average of 0.5 °C at the 1.5 °C GWL to 1.3 °C at the 4 °C threshold (Fig. 12). Model agreement for HWI is weak at 1.5 °C and 2 °C GWL but strengthens at 3 °C GWL. At 4 °C GWL, model agreement is strong across the entire country, with SNR values consistently exceeding 1 in all regions, indicating robust confidence in the projections.

3.3 Changes in precipitation-related extremes

Figure 13 projects changes in precipitation-related extremes across GWLs. Extreme rainfall indices show a slight increase compared to the 1995–2014 baseline across all regions. However, a large inter-model spread introduces uncertainty in the projections. Even under the Paris Agreement target of 1.5 °C GWL, notable increases in extreme precipitation are expected, while at higher warming levels of 3 °C and 4 °C, these changes become substantially more pronounced. Large inter-model spreads and outliers indicate considerable uncertainty, particularly at higher GWLs. The analysis indicates a potential for notable changes in extreme events beyond historical ranges, suggesting future precipitation patterns in Vietnam may differ considerably from past observations.

Annual maximum daily rainfall Rx1day shows a positive correlation with GWLs, as demonstrated by the upward trends in national averages (Fig. 14). The average increases in Rx1day are modest but consistent: approximately 6.7% (7.7 mm) at 1.5 °C GWL, 8.9% (10.3 mm) at 2 °C GWL, 12% (13.9 mm) at 3 °C GWL and reaching their maximum of around 13.8% (15.8 mm) at 4 °C GWLs. While these

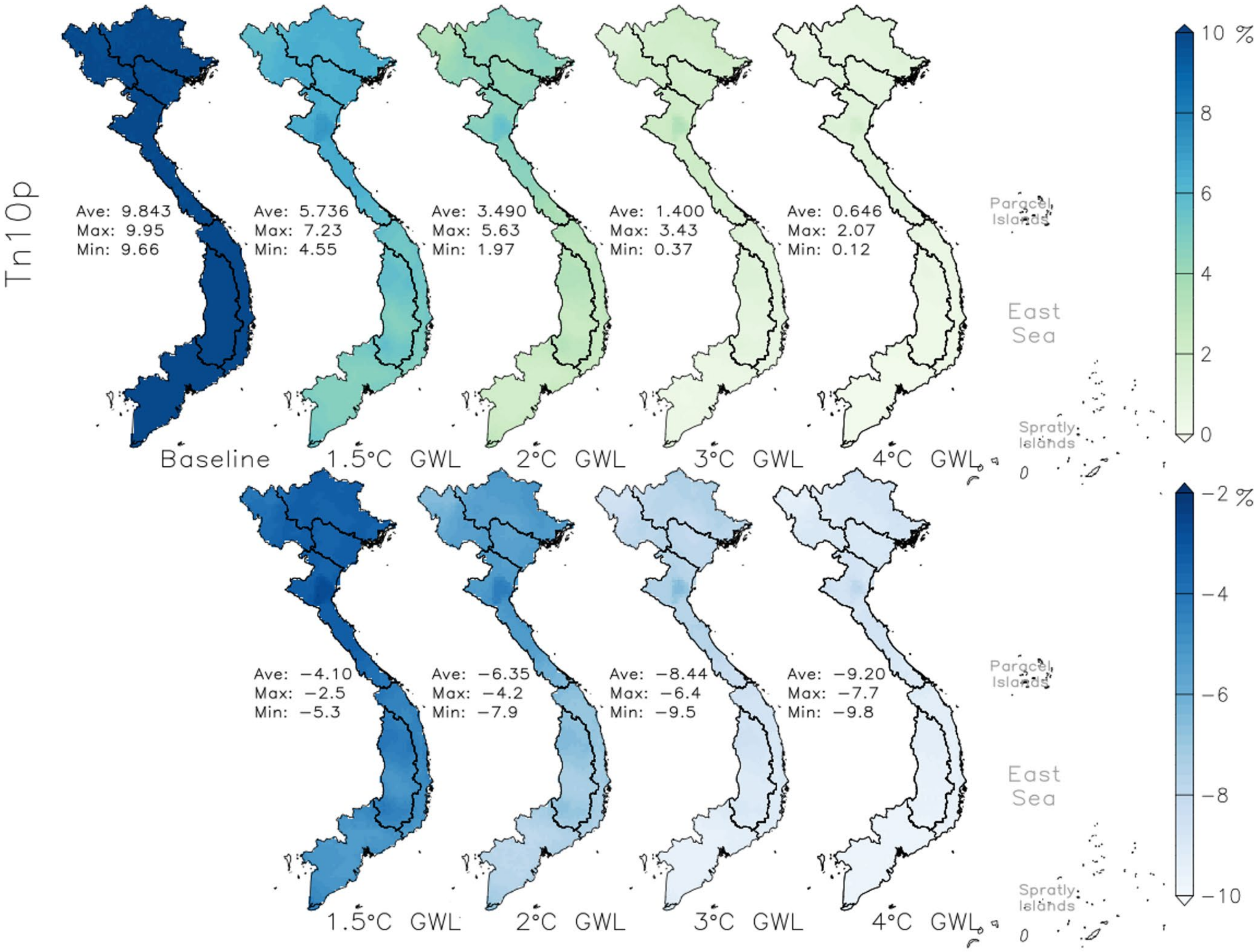

Fig. 9 Similar to Fig. 6 but forTN10p

increases may appear relatively small, they represent a systematic intensification of extreme precipitation events with rising global temperatures. This gradual trend suggests that even incremental increases in global warming could lead to measurable changes in precipitation patterns. The central regions (R4, R5) record the highest Rx1day averages, ranging from 192.5 mm at a 1.5 °C GWL to 205.1 mm at a 4 °C GWL (Table 4), with a projected increase of 6.5%–13.8% compared to the baseline. While the highest Rx1day values are consistently accumulated in the central regions, the increasing trend is more pronounced in the North (R1–R4), showing a 15.1% rise at the 4 °C GWL, compared to 11.4% in the South (R5–R7).

For Rx5day (Appendix B, Figure B2), the national average remains consistently 2.06 to 2.08 times higher than Rx1day, increasing gradually from 255 mm (1.5 °C GWL) to 273 mm (4 °C GWL). The distribution of Rx5day closely follows that of Rx1day, with the North once again experiencing the highest projected increase, ranging from 7.4% at a 1.5 °C GWL to 15.8% at a 4 °C GWL. However, while higher GWLs correlate with increased rainfall intensity, the trend remains uncertain due to low SNR values across regions, for both Rx1day and Rx5day. The low model agreement indicates substantial uncertainty in the magnitude and spatial distribution of future extreme rainfall events.

Very wet day precipitation R95pTOT shows a similar but considerably more subdued response to rising GWLs compared to extreme precipitation intensity (Fig. 15). At the national scale, R95pTOT exhibits only a modest increase relative to the baseline period, rising from approximately + 0.73% at 1.5 °C GWL to + 1.46% at 4 °C GWL. However, these national changes are associated with low model confidence due to substantial inter-model disagreement. Regionally, the changes are spatially heterogeneous to Rx1day and Rx5day. The South Central Coast region (R5)

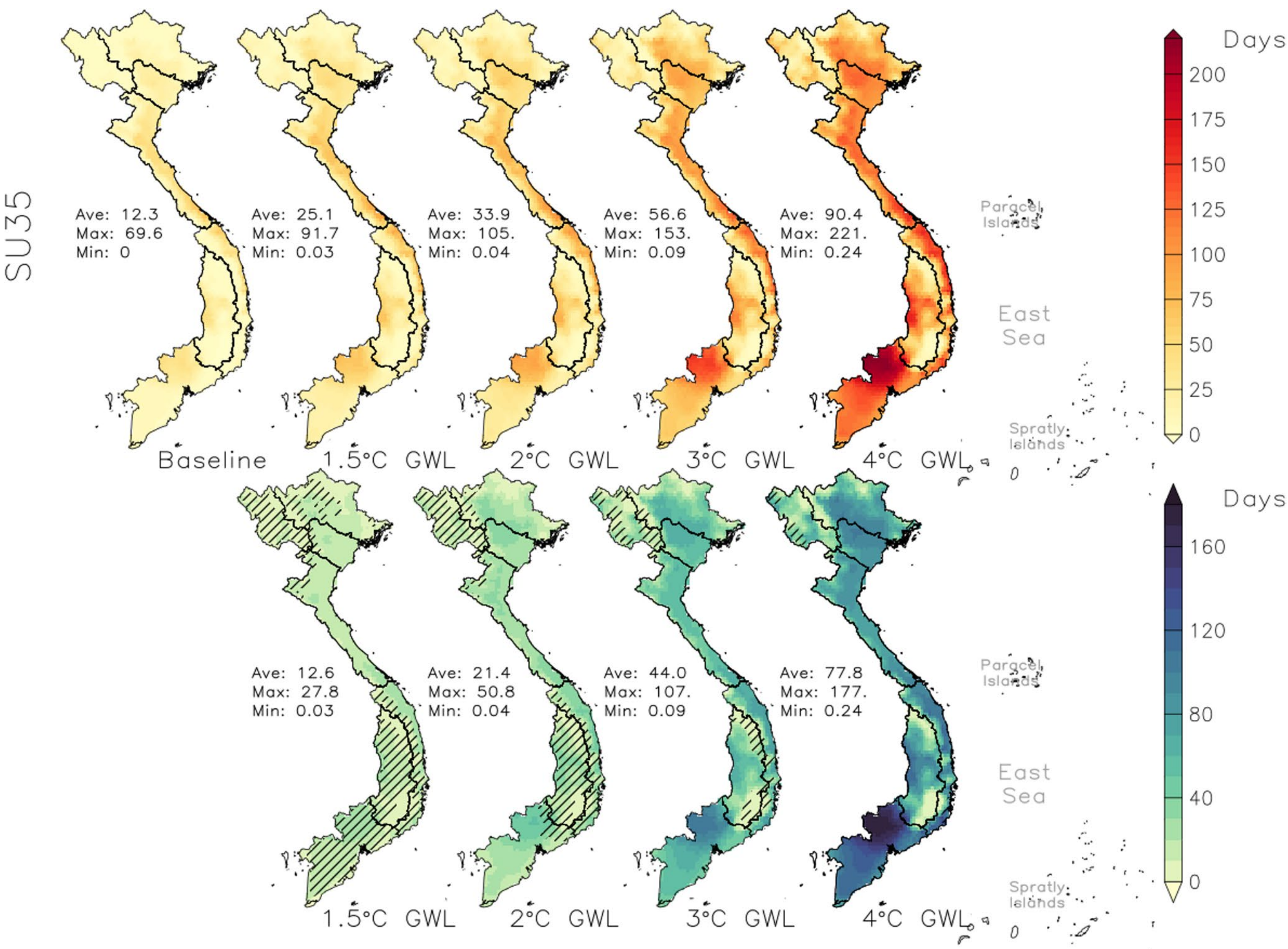

Fig. 10 Similar to Fig. 6 but for SU35

exhibits the largest increase, reaching approximately + 1.9% at the 4 °C GWL, while other regions display smaller and more variable responses.

Figure 16 reveals minimal changes in the frequency of heavy rainfall days across the country as GMST rises. At the national level, R50mm shows only a slight increase by 0.3 days at 1.5 °C GWL, gradually rising to 0.8 days at 4 °C GWL. These changes are barely noticeable and SNR values remain low for all regions. Regional analysis shows that the northwest region (R1) projects the largest increases in R50mm, though still modest: 0.6—0.7 days at 2 °C and 3 °C GWL, rising to 0.9 days under 4 °C GWL. The central regions (R4 and R5) consistently experience the highest frequency of R50mm events, averaging 7.4 to 8.4 days annually under 4 °C GWL - significantly above the national average of 5.1 days (Table 4). This pattern remains relatively stable across warming levels from 2.0 °C to 4 °C GWL. The southern region, particularly R7, shows the lowest frequency of heavy rainfall, with only 1.9—2.2 days across all GWLs and minimal changes of 0.2—0.5 days from baseline conditions.

The pattern of extremely heavy rainfall events (R100mm) mirrors that of R50mm, with negligible variations across all GWLs (Appendix B, Figure B3). These events are most frequent in the central regions, averaging 2.7—3.1 days annually, with a modest increase of 0.5 days projected at 4 °C GWL - slightly higher than the national average increase of 0.3 days. Despite projections showing slightly more extreme rainfall at higher GWLs, the differences between warming levels remain minimal, with no distinct trend emerging.

On the contrary, CDD is projected to significantly increase across Vietnam under all GWLs, as shown in Fig. 17. The MSMME results indicate that the national average CDD will gradually increase from a baseline of 50.2 days to 52.1 days at 1.5 °C GWL (+ 1.9 days), 52.2 days at 2 °C GWL (+ 2 days), and 53.9 days at 3 °C GWL (+ 3.7 days), before reaching 56 days at 4 °C GWL (+ 5.8 days). At 1.5 °C and 2 °C GWL, the North shows marginally

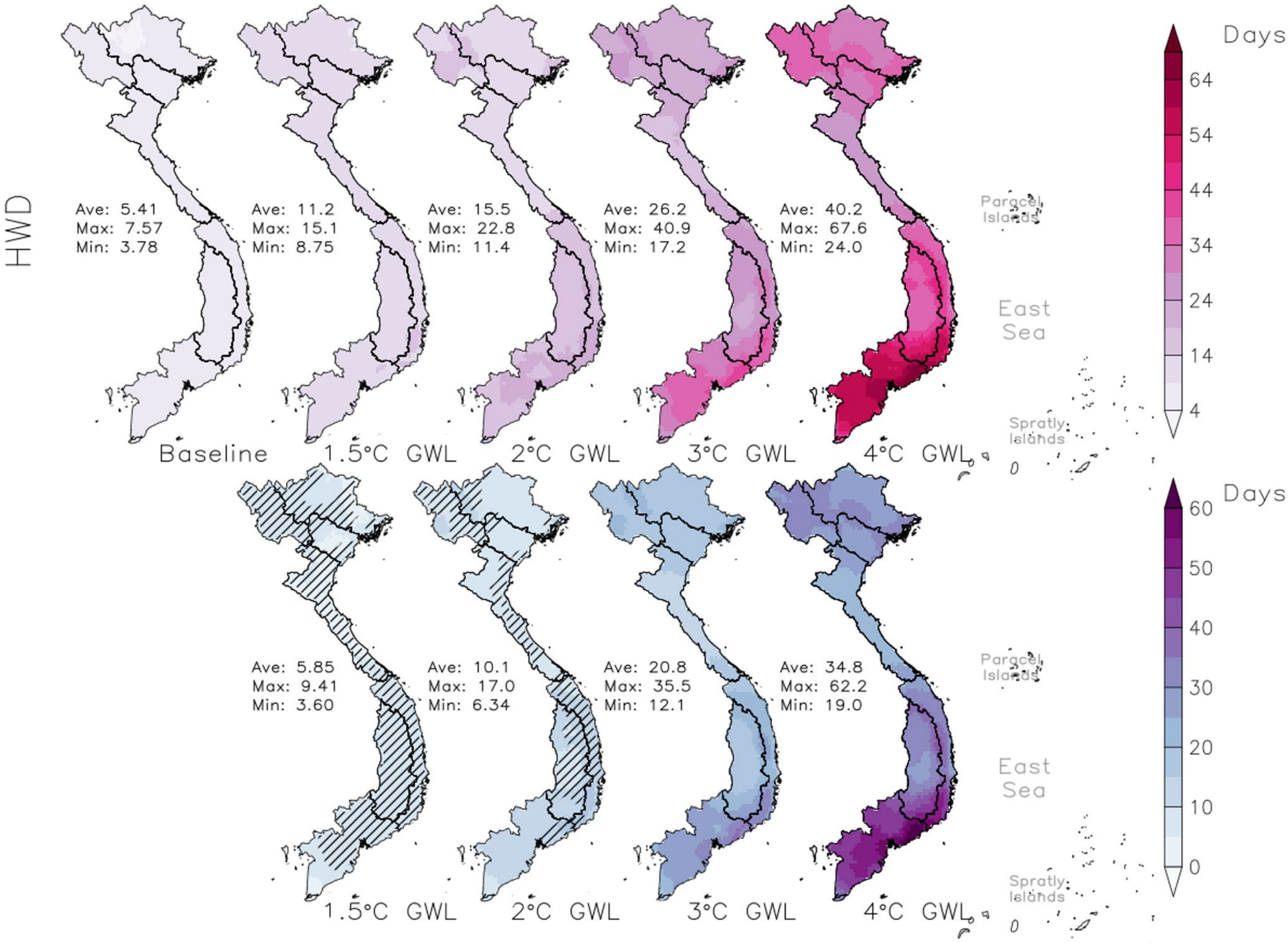

Fig. 11 Similar to Fig. 6 but for HWD

stronger CDD increases than the South (2.5 days compared to 1.2 days at 1.5 °C; 2.4 days compared to 1.3 days at 2 °C) (Table 4). This trend reverses under higher warming scenarios, with the South experiencing greater increases at 3 °C (3.6 days in the South, 3.2 days in the North) and 4 °C GWL (6.7 days in the South, 4.1 days in the North). Region R7 (Southern areas) maintains both the longest CDD durations (77—86.2 days across GWLs) and the most substantial increases (1.6—11.6 days) among all sub-climatic regions. While Region R4 (North Central) consistently shows the shortest CDD periods, it exhibits the second highest rate of increase after R7, with projections ranging from 2.7 days at 2 °C GWL to 5.2 days at 4 °C GWL. This regional variability indicates that different areas of Vietnam will experience varying levels of exposure to prolonged dry spells as global warming progresses. Model agreement on the increasing CDD trend is strong across all GWLs.

CWD shows a modest and statistically insignificant increase at the national level (Fig. 18), with projected changes at the national scale of 0.1 days at 1.5 °C GWL and 0.5 days at 4.0 °C GWL, respectively (Table 4). However, the spatial distribution of CWD change shows slight variations, reflecting uneven rainfall patterns across the country. The response of CWD differs among sub-climatic regions: it gradually decreases in R2, and R3, increases in R4 and R7, and shows mixed trends in R1, R5, and R6. These findings suggest that the decrease in CWD is not directly proportional to the extent of warming, but is affected by the uneven distribution of future rainfall changes across Vietnam.

Figure 19 shows a gradual increase in rainfall intensity (RI) as GWLs rise, similar to the trends observed in other extreme rainfall indices. Nationally, RI increases from 3.4% at the 1.5 °C GWL to 7.8% at the 4 °C GWL. Among the regions, the highest projected increase is observed in R4 (9.7% at the 4 °C GWL), followed by R5 (9.1%), while the lowest occurs in R7 (6%). This highlights the significant variability in RI increases across regions, with the central areas (R4 and R5) continuing to experience more pronounced changes compared to others.

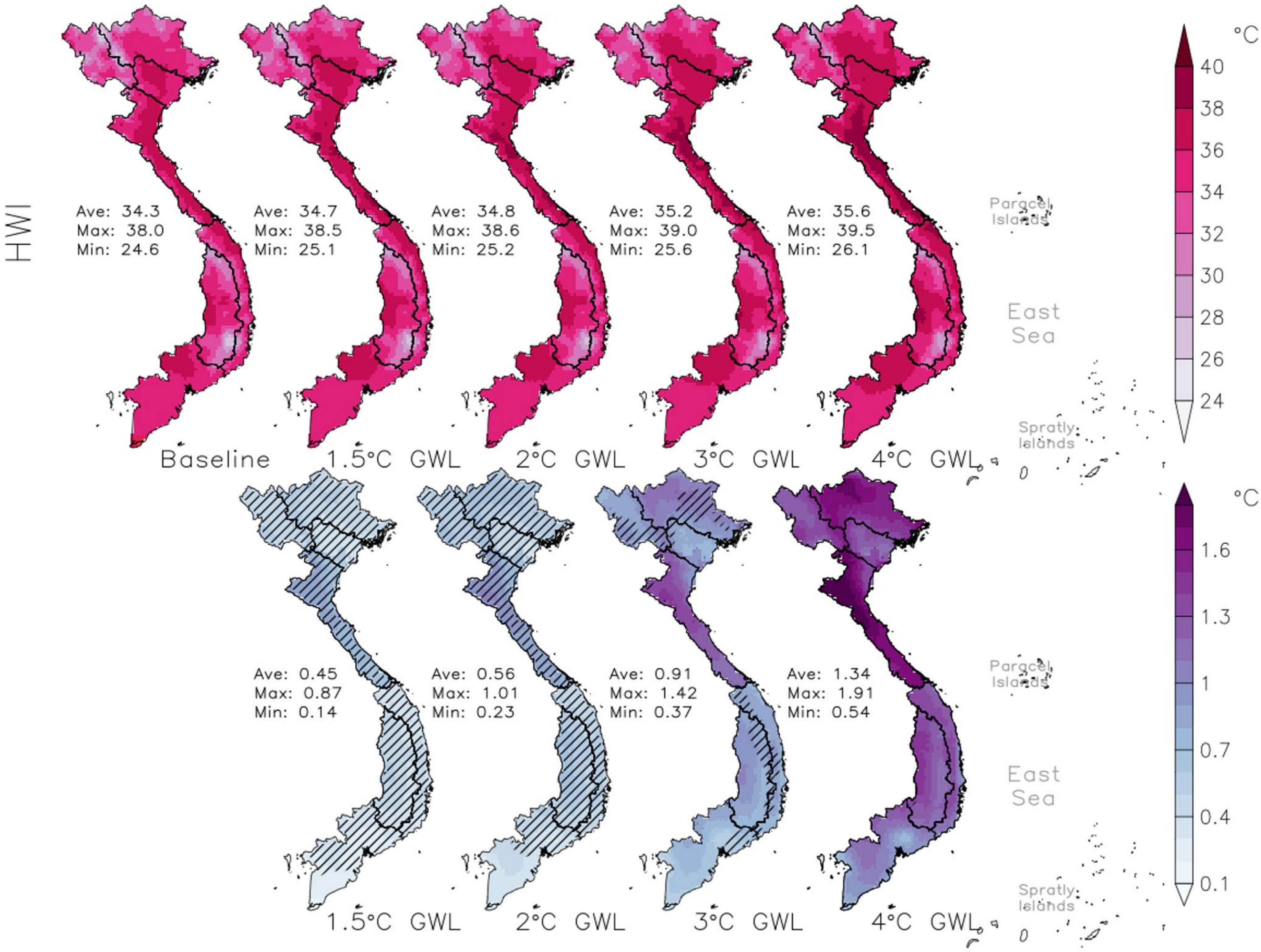

Fig. 12 Similar to Fig. 6 but for HWI

However, the SNR values for extreme precipitation indices are consistently below 1 across all regions. This indicates that the detected changes in rainfall characteristics are emerging from the background climate variability, but the signal is not yet strongly distinguishable from inter-model variability.

4 Conclusions

This study analyzed projected changes in temperature- and rainfall-related extremes in Vietnam under various GWLs ranging from 1.5 °C to 4 °C. By employing 33 models from the CMIP6-VN dataset developed in the previous phase of the GEMMES Vietnam project and analyzing five SSP scenarios, we assessed future changes in extremes in Vietnam using specific ETCCDI extreme climate indices. The uncertainty of these changes was quantified using SNR analysis. Changes in precipitation and temperature extremes at each GWL are evaluated relative to the baseline period of 1995–2014.

Several temperature extreme indices show significant increases across all GWLs. The maximum temperature of the hottest day (TXx) would rise by 1.5 °C and 2.2 °C on average at 2 °C and 3 °C GWL respectively, with larger increases in the northern than in the southern regions. Similarly, the projected annual percentage of warm days (TX90p) could reach 25.5% (resp.42% and 57.5%) on average at 2 °C GWL (resp. 3 °C and 4 °C GWL). SNR ratio appears to be strong since 1.5 °C GWL. Contrary to the pattern projected for TXx, the increase in TX90p would be more pronounced in southern regions, particularly in the Mekong River Delta and the Southeast, where TX90p could reach 56% on average at 3 °C GWL and 75.9% at 4 °C GWL. In this sub-region, hot days (TX > 35 °C) and very hot days (TX > 37 °C) could increase by 66 days/year (resp. 127 days/year) and 17 days/year (resp. 45 days/year) at 3 °C (resp. 4 °C) GWL. In the southeast, hot days could even

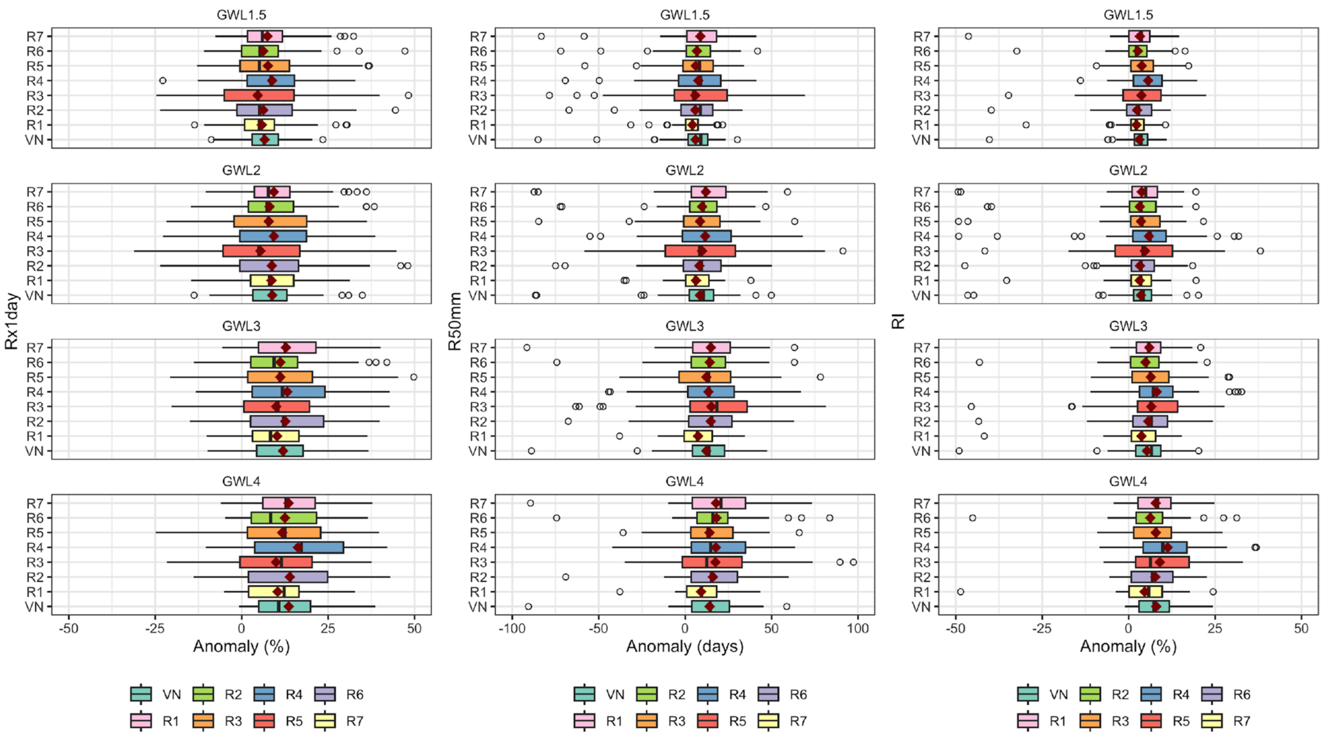

Fig. 13 Similar to Fig. 5 but for projected changes of Rx1day (left), R50mm (middle), and RI (right)

occur about 220 days/year at 4 °C GWL, indicating continuously hot conditions for about 7 months per year. Heatwave intensity is projected to remain relatively close to baseline values even at high GWLs, but heatwave duration would gradually increase, from an average of ~5 days at the country scale during the baseline period to about 40 days at 4 °C GWL. Hence, all projected trends in temperature extremes indicate that hot conditions that used to be relatively rare events will become more frequent and long-lasting events in future decades. Note that our study investigated the evolution of air temperature only and did not consider air humidity, a critical variable to assess heat stress. This issue has been investigated in another study (Nguyen-Le et al., 2026).

Extreme heat has already had significant negative impacts in Vietnam, however only a handful of studies have investigated the potential impacts of increasing hot conditions in future decades (Woillez, 2024). Our findings confirm that Vietnam will increasingly face extreme heat conditions and that this issue deserves more attention. If global GHG emissions remain unabated and the GWL exceeds 2 °C during this century, the magnitude and duration of hot conditions, especially in low-lying areas and southern regions, could significantly impact the well-being and prosperity of affected populations. Even in the medium term, if 2 °C GWL is reached by mid-century, such warmer conditions could have significant negative impacts on health and work capacity, with potential repercussions on the healthcare system, productivity, and income in various economic sectors. Direct negative impacts on crop productivity may occur if warm spells coincide with critical stages of plant development. Increased energy demand due to greater use of air-conditioning, as well as higher water demand for irrigation or household consumption, is also expected. Although quantitative assessments of extreme temperature impacts are challenging, the issue of increasing heat hazards in Vietnam needs to be taken into account in adaptation strategies.

While all climate models project warmer conditions in Vietnam at higher GWLs, the evolution of precipitation-related extreme indices remains uncertain. Average CMIP6-VN projections indicate a moderate increase of precipitation intensity: maximum 1-day precipitation (Rx1day) would increase by ~8.9% at 2 °C GWL to ~13.8% at 4 °C GWL on average. The largest increase – 9.3% (resp.13.4%) at 2 °C (resp. 3 °C) GWL - would occur in the North Central Region, a region which already experiences the highest Rx1day value over the baseline period and frequently faces flooding events. However, these average values hide a large inter-model spread at all GWLs, highlighting the high level of uncertainty. Similarly, maximum 5-day precipitation (Rx5day) and rainfall intensity are projected to increase by a few percentages on average, but the changes are not statistically significant. Projected changes in the annual number of heavy (>50 mm/day) or very heavy (>100 mm/day) precipitation days, as well as changes in the maximum number of consecutive wet days, are minimal and not significant. On the other hand, the annual maximum number of consecutive

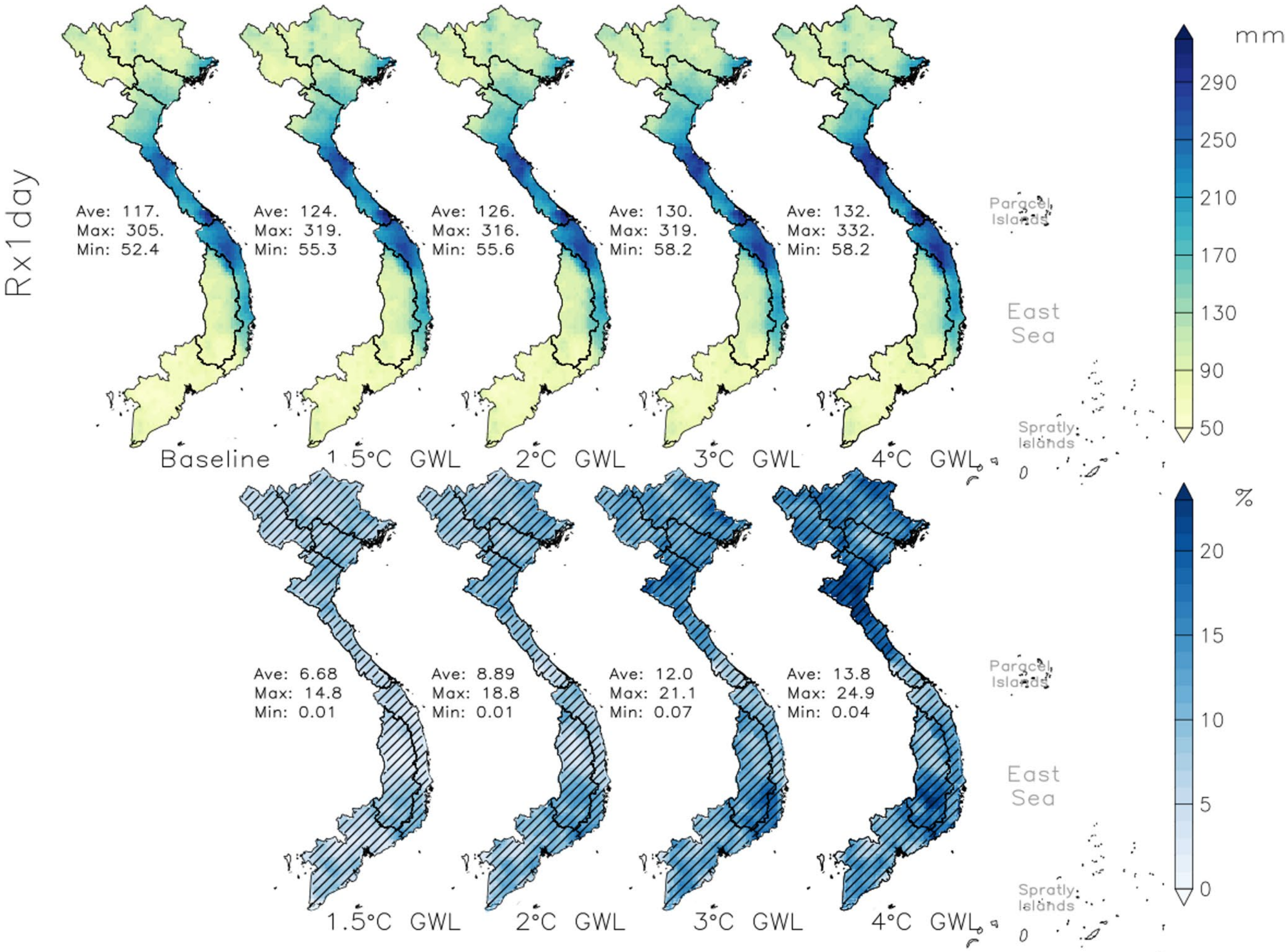

Fig. 14 Similar to Fig. 6 but for Rx1day

dry days (CDD) could significantly increase in all regions, with the largest increase in the North Central and the South, from 32 to 75 days respectively in the baseline period to 35 days (resp. 38 days) and 78 days (resp. 86 days) at 2 °C (resp. 4 °C) GWL.

The large inter-model spread in extreme precipitation projections and hence high level of uncertainty is not specific to Vietnam but an issue common to many world regions. While future developments in climate models may reduce the range of uncertainty in precipitation projections, current uncertainties remain a challenging issue to tailor efficient adaptation plans to extreme precipitation changes. Our findings illustrate that it is not possible to use the output of a single climate model as an input for infrastructure design to manage extreme precipitation and related flooding events. Historical trends in precipitation (total rainfall, Rx1day, and Rx5day) over the past four decades are also contrasted and uncertain (Espagne et al., 2021). Hence, adaptation decisions will need to be made in this context of high uncertainty. Different approaches have been suggested, such as "no regret" or flexible strategies (e.g. Hallegatte, 2009), which need to be further investigated in the context of Vietnam.

Global warming continues to be a pressing challenge that requires international efforts to reduce anthropogenic greenhouse gas emissions and to limit temperature rise. In this context, Vietnam must strengthen its preparedness to cope with the increasing frequency and intensity of extreme climate events. To support these efforts, further research is needed to assess the impacts of climate change on various aspects of society such as food security, water resources, and ecosystems. The CMIP6-VN dataset and the extreme analysis results from this study can provide valuable inputs for future research, contributing to effective adaptation and mitigation strategies in Vietnam.

Table 4 Similar to Table 3 but for precipitation-related extreme indices

Scenario	Region	Rx1day	Rx5day	R50mm	R100mm	R95pTOT	CDD	CWD	RI
	Unit	mm	mm	Days	Days	%	Days	Days	mm/day
GWL1.5	VN	124.3 (+7.7±17.4)	254.8 (+14.7±23.3)	4.7 (+0.3±0.9)	1.2 (+0.1±0.4)	32.9 (+0.7±4.4)	52.2 (+1.9±0.6)	25.2 (+0.1±0.6)	11.8 (+0.4±0.7)
	R1	110.8 (+7.7±13.4)	218.6 (+13.7±19)	4.9 (+0.5±0.8)	0.8 (+0.2±0.3)	34.1 (+0.8±3.7)	41 (+2.5±0.6)	19.8 (+0±0.6)	11.9 (+0.4±0.6)
	R2	95.3 (+5.6±11.7)	193.6 (+11.4±17)	4 (+0.4±0.7)	0.5 (+0.1±0.2)	31 (+1±4.8)	48.7 (+2.4±0.6)	27.3 (−0.3±0.6)	11.5 (+0.3±0.6)
	R3	136.9 (+10.7±20.4)	256 (+19.2±22.5)	5.1 (+0.3±0.8)	1.2 (+0.2±0.3)	38.6 (+0.9±3.8)	47.8 (+2.2±0.7)	15 (−0.1±0.6)	12.6 (+0.4±0.7)
	R4	192 (+13.9±27.6)	372.5 (+29.3±30.9)	7.1 (+0.3±1)	2.5 (+0.2±0.6)	40.9 (+0.9±3.4)	35.1 (+2.7±0.7)	15.9 (+0.2±0.6)	13.7 (+0.6±1)
	R5	193 (+9.3±32.9)	409.3 (+16.9±43)	7.8 (+0.3±1.4)	2.9 (+0.2±0.8)	39.3 (+0.6±3.4)	44.4 (+1.5±0.7)	20.6 (+0±0.6)	13.5 (+0.5±1.2)
	R6	106 (+6.3±16.2)	231.2 (+11.6±21.4)	3.8 (+0.3±0.9)	0.8 (+0.1±0.3)	28.5 (+0.6±5.4)	61.1 (+0.5±0.6)	35.2 (+0±0.6)	10.9 (+0.3±0.6)
	R7	71.4 (+3.9±9.2)	157.8 (+7.4±15.4)	1.9 (+0.2±0.5)	0.2 (+0±0.1)	25.2 (+0.5±5.7)	77 (+1.6±0.6)	32.4 (+0.5±0.6)	9.8 (+0.3±0.4)
GWL2	VN	126.2 (+10.3±20.1)	258.8 (+19.7±27.1)	4.8 (+0.5±1)	1.2 (+0.2±0.4)	33 (+0.8±4.8)	52.3 (+1.9±0.7)	25.4 (+0.3±0.7)	11.9 (+0.5±0.8)
	R1	112.4 (+9.6±15.3)	222.2 (+17.7±21.2)	5.1 (+0.6±1)	0.9 (+0.2±0.3)	34 (+0.8±5.4)	41 (+2.4±0.7)	20 (+0.3±0.7)	12 (+0.5±0.7)
	R2	96.7 (+7.2±12.3)	196.8 (+14.9±18.3)	4.1 (+0.5±0.8)	0.5 (+0.1±0.2)	31 (+1±5.9)	49 (+2.6±0.7)	27.5 (−0.1±0.6)	11.6 (+0.4±0.7)
	R3	136.6 (+11.7±22.8)	254.4 (+19.7±25.9)	5.2 (+0.4±1)	1.2 (+0.2±0.4)	38.5 (+0.9±5.2)	47.4 (+1.7±0.7)	15.1 (+0.1±0.6)	12.6 (+0.5±0.8)
	R4	193.3 (+16.5±33.3)	374.8 (+33.2±35.9)	7.2 (+0.5±1.2)	2.5 (+0.3±0.7)	41 (+1±3.2)	35.2 (+2.7±0.7)	16 (+0.4±0.7)	13.9 (+0.7±1.2)
	R5	196.5 (+14±39.8)	419 (+28.9±50.8)	7.9 (+0.4±1.8)	3 (+0.3±1)	39.5 (+0.9±2.9)	44.4 (+1.5±0.7)	20.7 (+0.1±0.7)	13.6 (+0.6±1.5)
	R6	108.4 (+9.1±18.7)	236.2 (+17.3±25.6)	3.9 (+0.4±1)	0.8 (+0.1±0.4)	28.8 (+0.9±5)	60.9 (+0.3±0.6)	35.4 (+0.2±0.7)	11 (+0.4±0.8)
	R7	73.3 (+5.8±10.6)	161.3 (+11±18.5)	2.1 (+0.4±0.6)	0.2 (+0.1±0.1)	25.3 (+0.6±5.6)	77.6 (+2.1±0.6)	32.8 (+0.8±0.6)	9.9 (+0.4±0.5)
GWL3	VN	130.1 (+13.9±22)	268.1 (+28.5±32)	5 (+0.6±1.1)	1.3 (+0.2±0.4)	33.3 (+1.2±4.4)	53.9 (+3.6±0.7)	25.4 (+0.3±0.7)	12 (+0.7±1)
	R1	115.7 (+13.1±17.7)	229.2 (+25±22.8)	5.2 (+0.7±1)	0.9 (+0.3±0.4)	34.3 (+1.1±2.8)	41.6 (+3.1±0.7)	19.9 (+0.1±0.7)	12.1 (+0.7±0.8)
	R2	99.2 (+10±13.9)	203.9 (+22.4±21.7)	4.3 (+0.7±0.9)	0.6 (+0.2±0.3)	31.4 (+1.4±4.6)	49.2 (+3±0.6)	27.5 (−0.2±0.7)	11.7 (+0.6±0.8)
	R3	142.6 (+17.1±29)	268.6 (+32.9±29.1)	5.3 (+0.5±1.1)	1.3 (+0.3±0.5)	39.1 (+1.4±3.3)	48.3 (+2.7±0.7)	15.1 (0±0.7)	12.8 (+0.7±1.1)
	R4	199.8 (+23.6±38.3)	388 (+47.5±41.1)	7.3 (+0.5±1.3)	2.6 (+0.3±0.7)	41.4 (+1.4±3)	36.5 (+4.1±0.8)	16 (+0.4±0.7)	14 (+0.9±1.4)
	R5	201.9 (+18.3±36.5)	436 (+44.3±60)	8.2 (+0.7±1.7)	3.2 (+0.4±0.9)	39.9 (+1.3±2.7)	45.8 (+2.8±0.7)	21 (+0.4±0.8)	13.9 (+0.9±1.4)
	R6	112.7 (+12.6±19.7)	247.3 (+27.2±33.4)	4.2 (+0.7±1.2)	0.9 (+0.2±0.4)	29.1 (+1.3±5.9)	62.8 (+2.1±0.6)	35.6 (+0.3±0.7)	11.2 (+0.6±0.9)
	R7	74.3 (+6.9±11.6)	163.6 (+13.4±21.7)	2.1 (+0.4±0.7)	0.2 (+0.1±0.2)	25.5 (+0.8±6.9)	81.5 (+6±0.6)	32.8 (+0.7±0.7)	10 (+0.4±0.6)
GWL4	VN	132.1 (+15.8±22.2)	272.5 (+33.3±32.5)	5.1 (+0.8±1.2)	1.3 (+0.3±0.5)	33.6 (+1.5±6.4)	56.1 (+5.6±0.7)	25.5 (+0.5±0.7)	12.2 (+0.9±1.1)
	R1	116.9 (+15.1±18.3)	232.4 (+30.4±24.5)	5.3 (+0.9±1.1)	1 (+0.3±0.4)	34.5 (+1.3±4.1)	42.6 (+3.8±0.7)	20 (+0.3±0.7)	12.3 (+0.8±0.9)
	R2	101.7 (+12.6±15.9)	206.7 (+27±22.8)	4.5 (+0.9±1)	0.7 (+0.2±0.3)	31.6 (+1.5±7)	50.6 (+4±0.7)	27.6 (−0.1±0.6)	11.9 (+0.8±0.9)
	R3	142.3 (+17.4±26.8)	267.1 (+34.2±30.6)	5.3 (+0.6±1.1)	1.3 (+0.3±0.5)	39.2 (+1.5±4.7)	49.3 (+3.5±0.8)	15.2 (+0.2±0.7)	12.8 (+0.9±1.1)
	R4	204.9 (+30.7±40.3)	399.1 (+61.6±42.3)	7.4 (+0.7±1.5)	2.7 (+0.5±0.8)	41.7 (+1.6±3.9)	37.8 (+5.2±0.8)	16 (+0.5±0.7)	14.3 (+1.3±1.6)

Table 4 (continued)

Scenario	Region	Rx1day	Rx5day	R50mm	R100mm	R95pTOT	CDD	CWD	RI
	R5	205.1 (+18.5±36.6)	441.1 (+43.5±56.8)	8.4 (+0.8±1.8)	3.3 (+0.5±1)	40.5 (+1.9±3.6)	48.1 (+5±0.7)	21 (+0.4±0.7)	14.3 (+1.2±1.6)
	R6	114.7 (+14±19.5)	251.1 (+30.9±30.7)	4.3 (+0.9±1.2)	1 (+0.3±0.4)	29.5 (+1.6±8.6)	64.8 (+4.3±0.6)	35.5 (+0.3±0.7)	11.4 (+0.8±1)
	R7	74.1 (+7±10.8)	165.5 (+14.7±23.5)	2.2 (+0.5±0.7)	0.2 (+0.1±0.1)	25.8 (+1.1±10.7)	86.2 (+10.6±0.6)	33.2 (+1.1±0.6)	10.1 (+0.6±0.7)

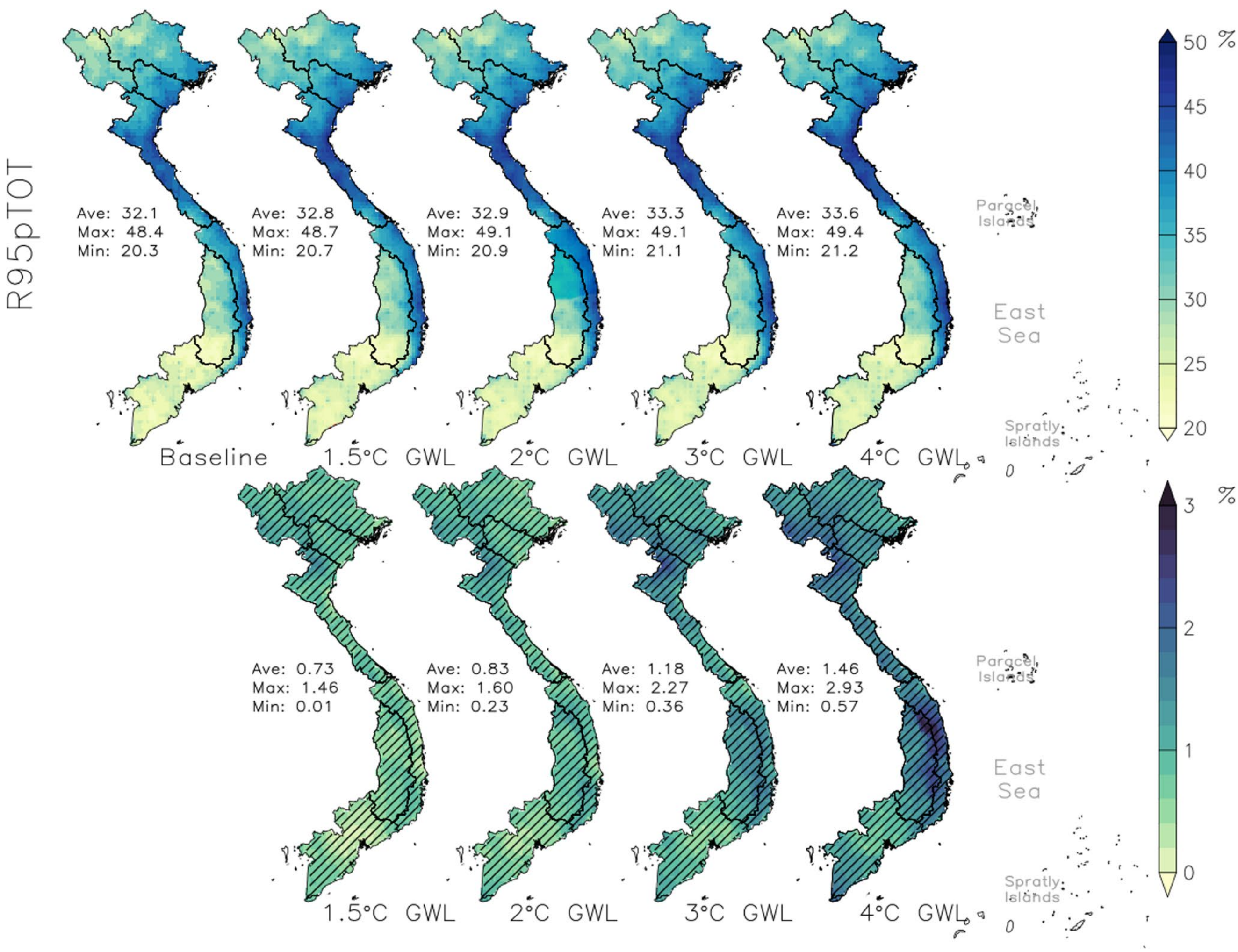

Fig. 15 Similar to Fig. 6 but for R95pTOT

5 Future research direction

The substantial inter-model spread in precipitation projections identified in this study underscores a critical challenge for climate adaptation planning in Vietnam. While the CMIP6-VN dataset has been developed using statistical downscaling and bias correction techniques, these approaches primarily address systematic biases in model outputs without fundamentally reducing projection uncertainty. In addition, due to data availability, the ensemble composition varies slightly across variables and SSP scenarios. While very high climate sensitivity models were excluded based on existing literature, some differences in ensemble membership may still influence the spread of projected responses, particularly for precipitation extremes. Further efforts toward ensemble harmonization could be explored in future studies. Recent methodological advances, particularly the "Emergent Constraint" framework, suggest

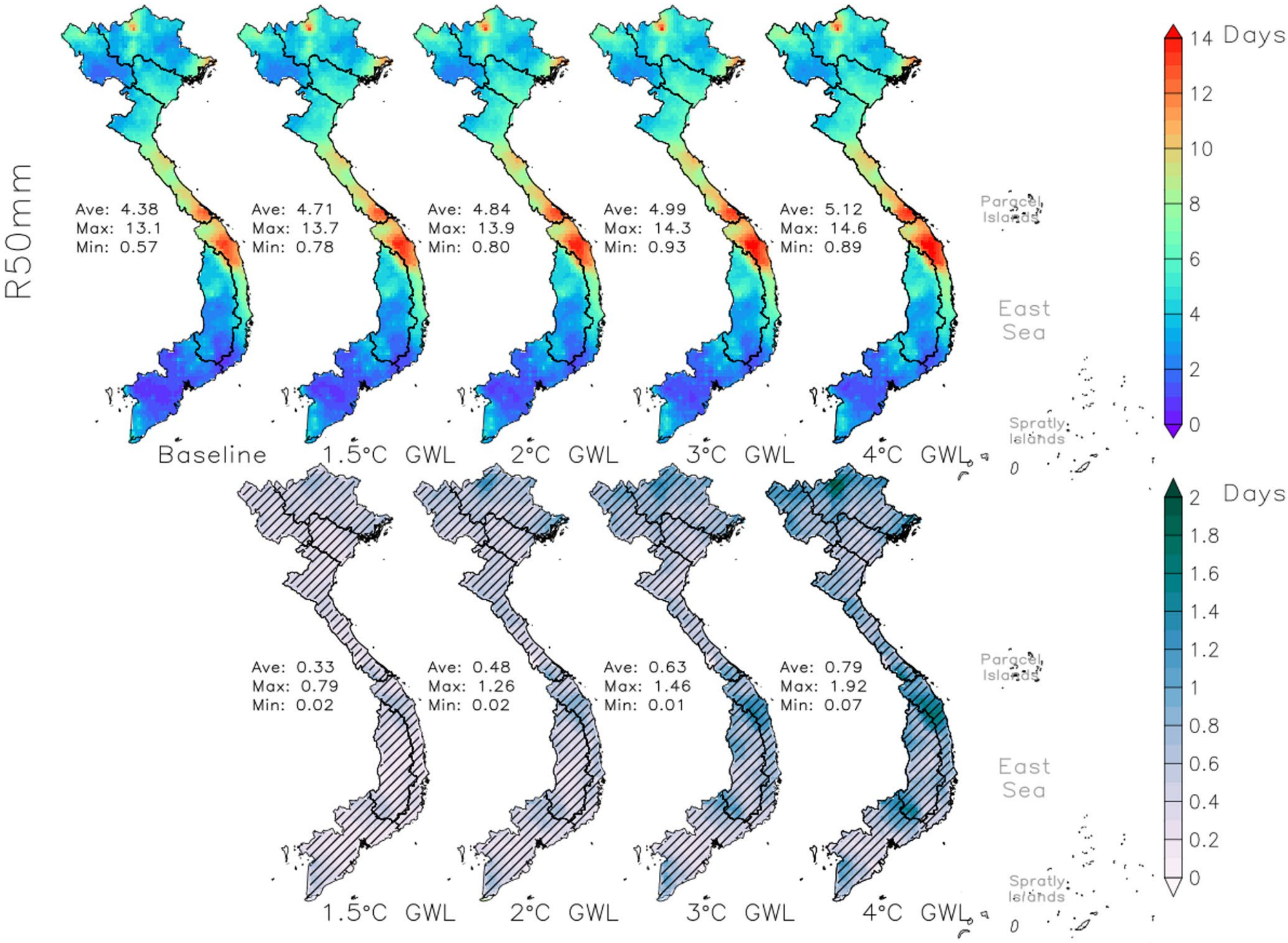

Fig. 16 Similar to Fig. 6 but for R50mm

alternative pathways for constraining future projections and narrowing uncertainty ranges. This framework involves investigating physical relationships between models' ability to reproduce observed climate features and their projections of future change (Hall et al., 2019; Williamson et al., 2021). For Vietnam, potential applications could examine whether models that better capture monsoon circulation patterns, land-sea thermal dynamics, or temperature-precipitation relationships also show consistent tendencies in their future projections. Establishing such physically-grounded connections could provide a basis for weighting or selecting models in ways that reduce the projection spread observed in this study (Chai et al., 2022, 2025a, 2025b, 2025c; Zhang et al., 2022b; Sansom et al., 2017). However, developing and validating these constraints for regional applications, particularly in topographically complex and monsoonal climates like Vietnam's, remains an open research challenge. Future work addressing these methodological questions could enhance the scientific foundation for climate risk assessment and adaptation decision-making in Vietnam.

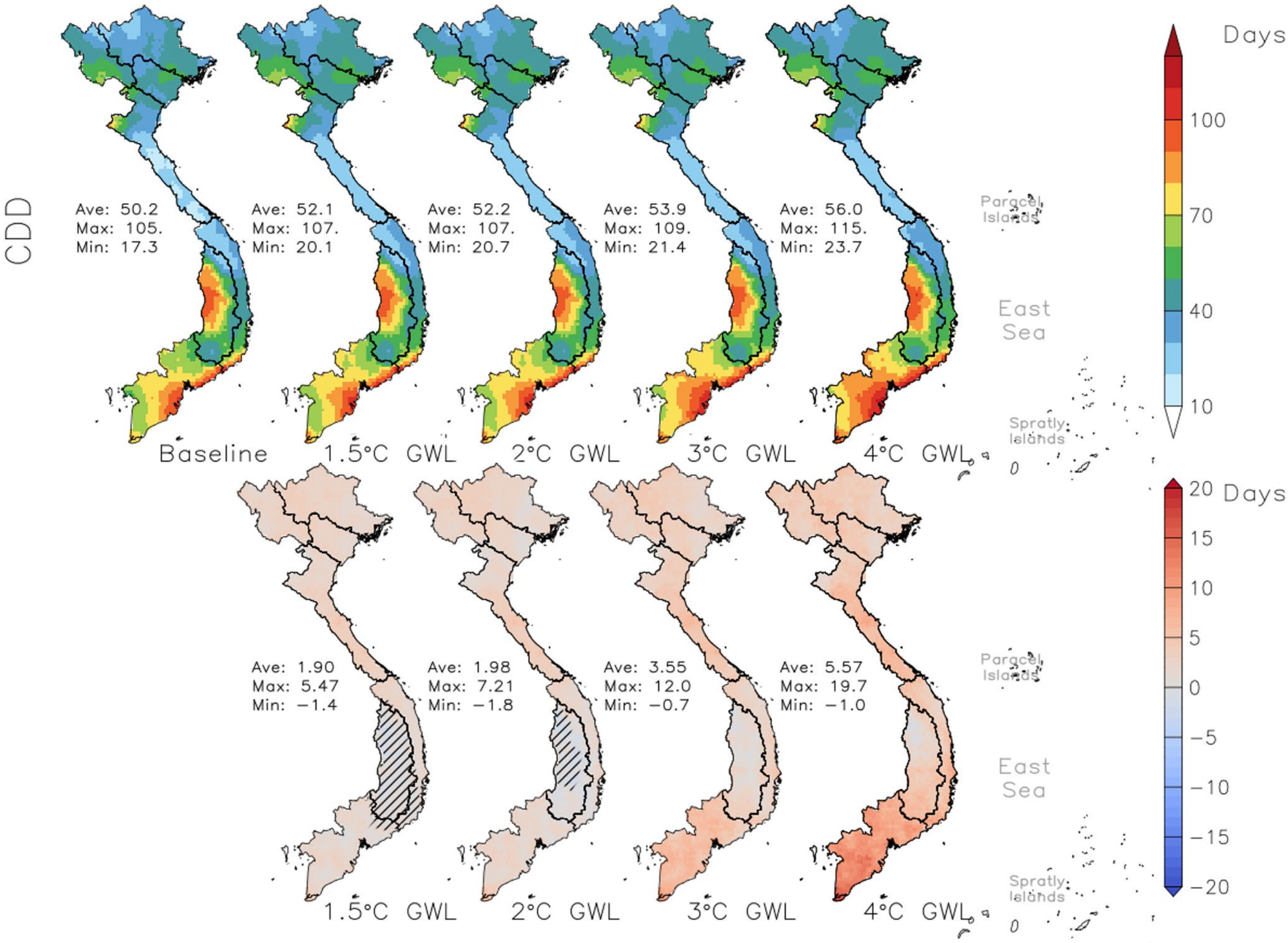

Fig. 17 Similar to Fig. 6 but for CDD

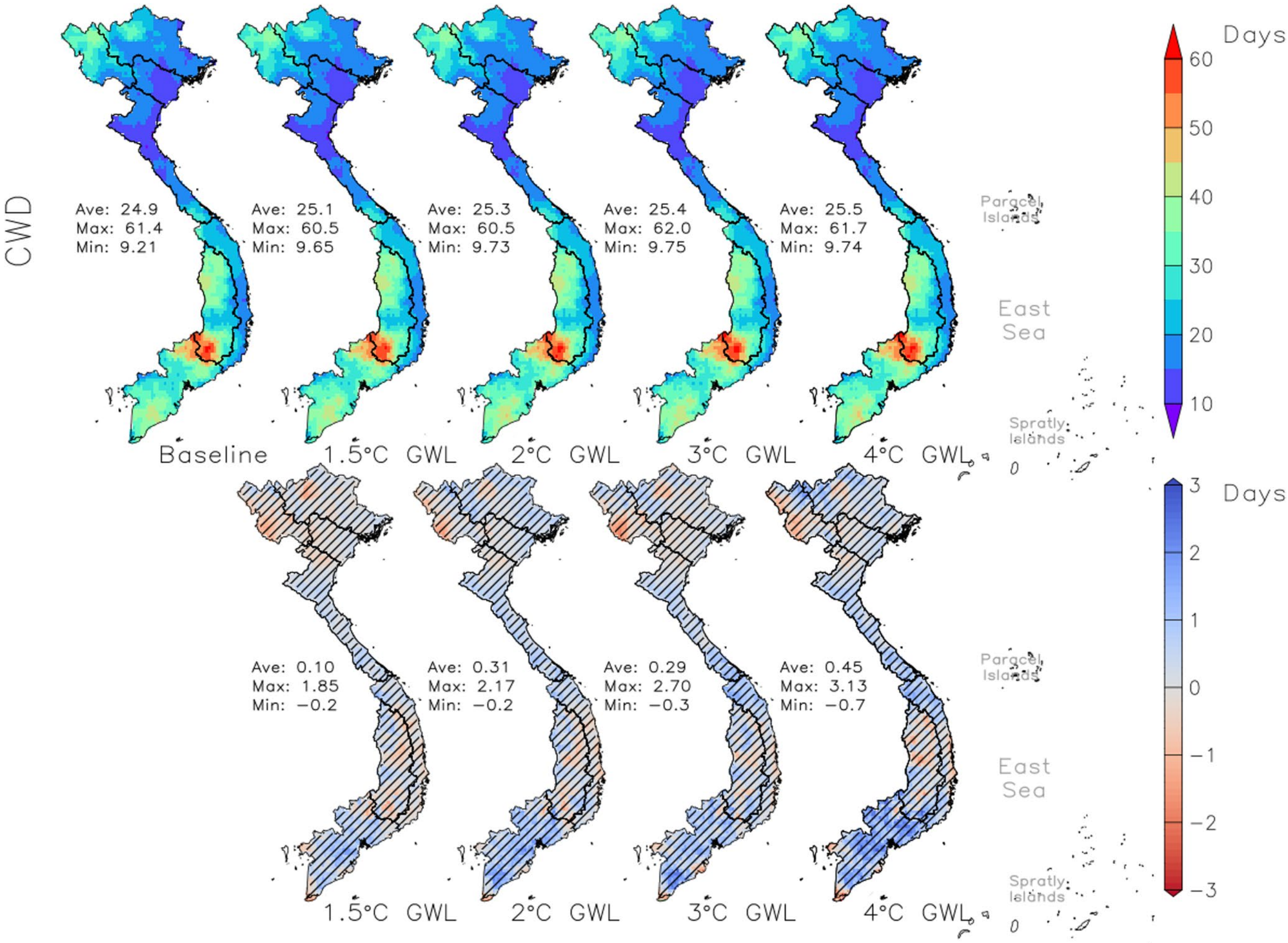

Fig. 18 Similar to Fig. 6 but for CWD

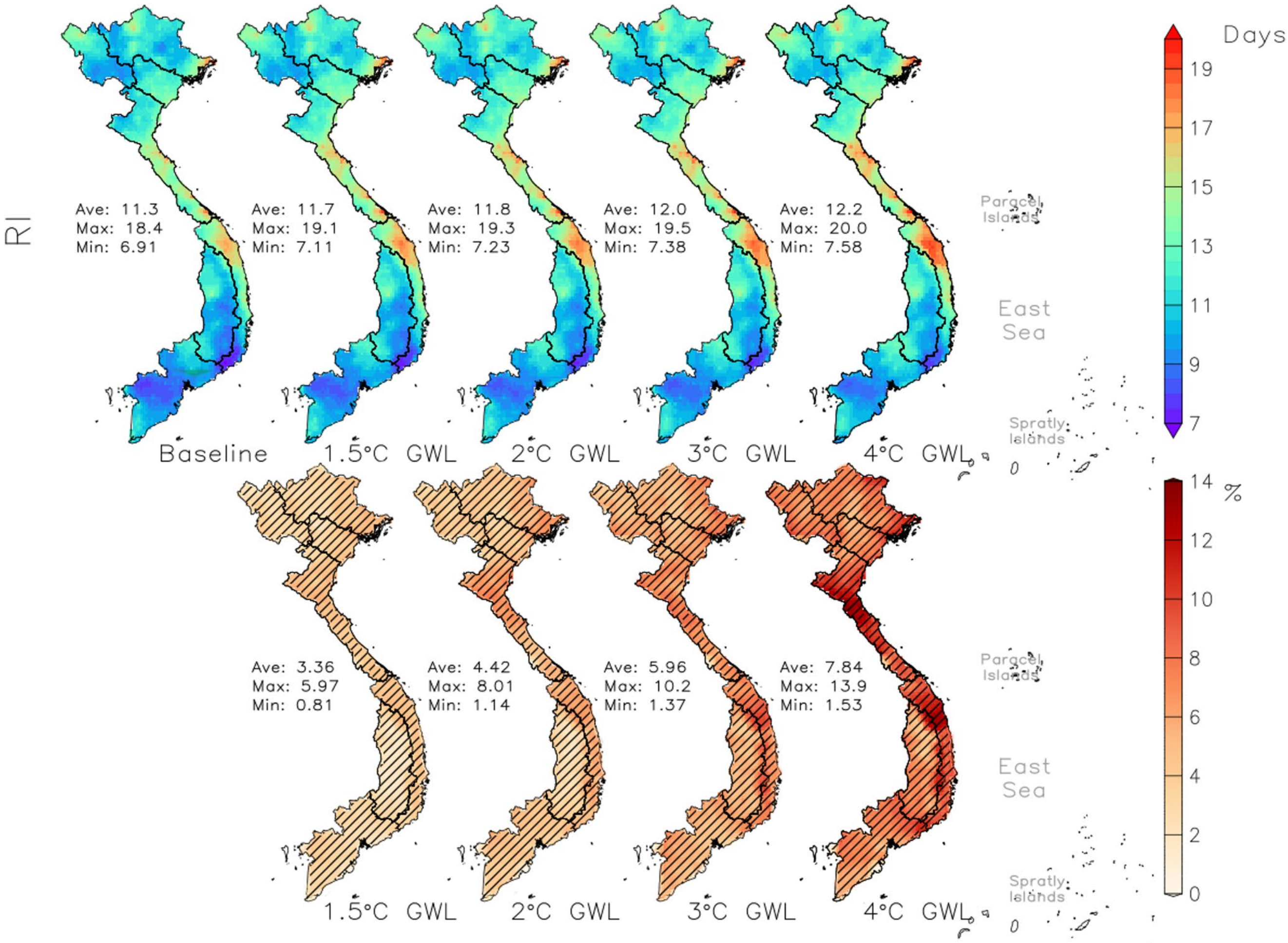

Fig. 19 Similar to Fig. 6 but for RI

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Author contributions QT-A conceptualized the study, conducted the simulations, and wrote the manuscript. ThN-D and M-NW provided guidance and analytical support. TN-X contributed to data processing and manuscript revision. DN-L and TuN-D contributed additional analyses, visualization, and further improvements to the study beyond the original AFD preprint version. All authors read and approved the final manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests. A preprint of this work has been published at https://www.afd.fr/en/ressources/changes-temperature-and-rainfall-extremes-vietnam-under-progressive-global-warming-levels under a Creative Commons license.

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