

Evaluating Drought Evolution in Vietnam Using Cmp6-Vn Climate Projections

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Abstract: This study evaluates drought evolution across Vietnam's seven climatic sub-regions from 1985 to 2099 using the one-month Standardized Precipitation Evapotranspiration Index (SPEI) derived from the 10-km resolution CMIP6-VN dataset. Three Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, SSP5-8.5) were analyzed for near-future (2015–2039), mid-century (2040–2069), and far-future (2070–2099) periods, with potential evapotranspiration estimated via the Hargreaves-Samani method. Mann-Kendall trend tests and signal-to-noise ratio (SNR) analyses assessed drought intensity, frequency, and severity. Temperature projections indicate consistent warming, with national averages increasing by 1.4°C (SSP1-2.6), 2.6°C (SSP2-4.5), and 4.5°C (SSP5-8.5) by century's end relative to the 1985–2014 baseline, with northern regions experiencing enhanced warming (up to 5.1°C in the Northeast) compared to southern regions (4.0°C in the Southeast). Precipitation is projected to increase across all scenarios, with SSP2-4.5 showing the largest rise (7.2% by 2070–2099), though with greater uncertainty ($\pm 20\%$) compared to temperature projections. Despite rising temperature and precipitation, drought tendencies vary non-linearly due to amplified evapotranspiration outpacing precipitation gains, with northern and central regions showing prolonged drying under SSP1-2.6 early-century, while southern regions stabilize due to balanced wet-dry cycles. Drought analysis reveals dynamic hydroclimatic variability: near-term (2015–2039) drying trends are most pronounced under SSP1-2.6 with extended moderate droughts, while mid-century (2040–2069) shifts to wetter conditions across all SSPs but most evidently in SSP1-2.6; late-century projections show modest SPEI increases with stronger wetting in northern regions under low-emission SSP1-2.6, contrasted by higher inter-model uncertainty and potential intensification in SSP5-8.5 due to amplified evapotranspiration-precipitation feedbacks. Drought intensity increases by up to 22.7% in southern Vietnam by 2015–2039 under SSP2-4.5, while frequency and severity exhibit non-monotonic trends, with notable increases in central regions (up to 15.7 months/event under SSP2-4.5). These findings underscore the need for adaptive irrigation and water management strategies to mitigate intensified drought impacts on Vietnam's agriculture, particularly in central and northern regions.

Keywords: CMIP6-VN, Drought, Vietnam, global warming, disaster

1. Introduction

Drought represents one of the most devastating natural hazards globally, affecting approximately 55 million people annually and causing economic losses exceeding \$124 billion worldwide (Wilhite et al., 2014). The results show that a high percentage of land area is experiencing significant drought intensification of 65.1%, 89.9%, and 99.8% under Shared Socioeconomic Pathways (SSP) 126, SSP245, and SSP585 scenarios, respectively (Xu et al., 2024). Vietnam, located in Southeast Asia's monsoon-dominated climate system, faces particularly severe drought challenges due to its complex topography, extensive coastline, and high dependence on agriculture. The country experienced devastating droughts during 2015–2017, affecting over 1.8 million people and causing agricultural losses exceeding \$1.6 billion (UNDRR, 2019). Drought exposure is slightly lower but still significant as highlighted by the severe drought of 2015–2017 (World Bank, 2021). Vietnam's vulnerability to drought is exacerbated by its high population density in rural areas, where approximately 66% of the population depends on agriculture for their livelihoods, making drought impacts particularly severe for food security and economic stability (GSO, 2020).

Climate change projections indicate intensifying drought patterns globally and regionally. The Intergovernmental Panel on Climate Change (IPCC, 2021) projects that many regions will experience more frequent and severe droughts under various warming scenarios. Literature studies generally indicate a trend toward more severe droughts in most areas, with China notably identified as a hotspot for these

intensification (Xu et al., 2024). Southeast Asia, including Vietnam, is projected to experience significant changes in precipitation patterns and temperature regimes. The CMIP6 multimodel ensemble mean projects a warming (wetting) of 1.99–4.29 °C (9.62–18.43%) in the 21st century (Nguyen-Ngoc-Bich et al., 2021). Contrary to the clear increasing temperature trends across all models, the future projection based on downscaled CMIP6 dataset shows a slight increasing precipitation trend over entire Vietnam in the late 21st century with much larger uncertainties (Tran-Anh et al., 2023). These projections suggest complex interactions between rising temperatures and changing precipitation patterns that could fundamentally alter drought characteristics in Vietnam.

Recent advances in climate modeling have enabled more robust assessments of future drought conditions using the latest generation of global climate models developed under the Coupled Model Intercomparison Project Phase 6 (CMIP6). Compared to earlier generations, CMIP6 models have shown improved performance in reproducing historical drought patterns and hydroclimatic variability (Cook et al., 2020; Ukkola et al., 2020). However, due to the complex interactions between drought and various climatic drivers, significant uncertainty remains regarding how drought characteristics will evolve under future climate change. Drought, as a persistent and widespread natural hazard, poses substantial risks to agriculture, ecosystems, and human livelihoods. With the release of the CMIP6 datasets, multiple model outputs have been evaluated against observational records to validate their skill in simulating drought-related variables (Wang et al., 2021). Global projections using CMIP6 consistently indicate an increase in drought severity and duration, particularly under high-emission scenarios, across many continental regions (Marvel et al., 2019).

Previous studies on drought assessment in Vietnam and the broader Southeast Asia region have primarily relied on earlier Coupled Model Intercomparison Project Phase 5 (CMIP5) outputs or limited subsets of CMIP6 data. For instance, using CMIP5-based CORDEX-SEA downscaled data, Nguyen-Ngoc-Bich et al. (2021) projected that droughts in Vietnam would become more widespread, particularly in southern regions under RCP8.5 scenarios, with increased likelihood of extreme events. Similarly, in the Lower Mekong River Basin, which includes parts of Vietnam, Tuong et al. (2025) analyzed CMIP6 projections and found potential increases in drought duration and severity due to altered precipitation patterns. More recent efforts incorporating CMIP6 have focused on specific areas, such as the Ca River Basin, where Shin et al. (2024) used an ensemble of 27 CMIP6 models to project heightened drought risks under multiple SSP scenarios, emphasizing drier conditions in the dry season. At a regional scale in Southeast Asia, Mondal et al. (2021) employed CMIP6 multimodel ensembles to forecast intensified drought conditions over the 21st century, with greater severity under high-emission pathways, while Tangang et al. (2017) highlighted projected changes in drought characteristics, including longer durations in monsoon-dependent areas. These studies demonstrate a growing body of evidence for worsening droughts but often rely on coarser resolutions or focus on sub-national scales.

In Vietnam, the application of CMIP6 data in drought projection studies has only recently begun and remains limited. Few studies have analyzed drought characteristics using CMIP6 scenarios, and comprehensive assessments are still lacking. Given the inherent uncertainty in climate change projections, employing a multi-model ensemble approach is essential to improve the robustness of future drought assessments (Stojanovic et al., 2024). Some efforts have examined future drought characteristics using CMIP6 ensembles over broader regions such as South Asia (Nguyen-Ngoc-Bich et al., 2022), while regional studies have focused on the Mekong River Basin (Tuong et al., 2025) and specific river basins within Vietnam (Pham and Vo, 2022). However, national-scale analyses remain scarce, and existing research has primarily concentrated on near-term projections. As a result, the full potential of CMIP6 models for assessing long-term drought risks through the end of the 21st century has yet to be fully explored in the Vietnamese context.

Significant knowledge gaps remain in drought projection research for Vietnam. Most existing studies focus on mid-century projections and lack assessments extending to 2100, limiting their relevance for long-term adaptation. The use of CMIP6 models is still limited, with many relying on CMIP5 or small subsets of CMIP6 outputs. Additionally, most projections lack high-resolution, nationwide coverage, instead targeting specific basins or provinces. Many studies continue to use precipitation-only indices like the Standardized Precipitation Index (SPI), which fail to account for rising evapotranspiration driven by increasing temperatures. In contrast, the Standardized Precipitation Evapotranspiration Index (SPEI) incorporates both precipitation and temperature, providing a more accurate assessment of drought under climate change (Vicente-Serrano et al., 2010).

This study pioneers a comprehensive national assessment of drought trends across Vietnam by

leveraging the state-of-the-art Coupled Model Intercomparison Project Phase 6 (CMIP6) outputs, with a particular emphasis on the innovative CMIP6-VN high-resolution downscaled dataset (Tran-Anh et al., 2023). Unlike previous studies that predominantly relied on coarser CMIP5 models or limited CMIP6 subsets, this research harnesses the advanced capabilities of CMIP6, which offers enhanced representation of hydroclimatic variability, improved parameterization of physical processes, and better alignment with observed drought patterns (Mondal et al., 2021; Zhao and Dai, 2022). The CMIP6-VN dataset, specifically developed for Vietnam, provides unprecedented 10-km resolution projections, incorporating sophisticated bias correction techniques and regional calibration tailored to Vietnam's complex topography and monsoon-driven climate. These advancements significantly improve accuracy over global CMIP6 models and earlier downscaled datasets, enabling precise spatial and temporal analysis of drought dynamics across Vietnam's diverse climatic zones. By employing the Standardized Precipitation Evapotranspiration Index (SPEI), which integrates temperature-driven evapotranspiration, this study captures drought characteristics under climate warming more realistically than precipitation-only indices like the Standardized Precipitation Index (SPI) used in prior works (Vicente-Serrano et al., 2010). Covering near- to far-future projections (2015–2100), the analysis utilizes a multi-model ensemble approach to address uncertainties across Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, SSP5-8.5), providing robust insights for both short- and long-term adaptation planning. The findings offer a transformative understanding of future drought patterns, filling critical gaps in national-scale, high-resolution assessments and supporting evidence-based strategies for sustainable water resource management and agricultural resilience in Vietnam.

2. Data and Methods

2.1. Study area

Vietnam is located in Southeast Asia (8°2'N–23°23'N, 102°8'E–109°28'E), covering 331,212 km² with diverse topography ranging from mountainous terrain to coastal plains and river deltas. The country experiences a tropical monsoon climate dominated by the East Asian monsoon system, with distinct wet (May–September) and dry (December–April) seasons. Annual precipitation varies significantly from 800 mm in semi-arid central regions to over 3,000 mm in northern mountains, while mean annual temperatures range from 21°C in northern highlands to 27°C in southern lowlands. The pronounced seasonality and spatial precipitation variability make Vietnam particularly vulnerable to drought during extended dry periods or delayed monsoon onset. This study analyzes drought across Vietnam's seven sub-climatic regions, delineated based on distinct climate patterns and topographic features ((Fig. 1): Northwest (R1), Northeast (R2), Red River Delta (R3), North Central (R4), South Central (R5), Central Highland (R6), and South (R7) (Fig.1).

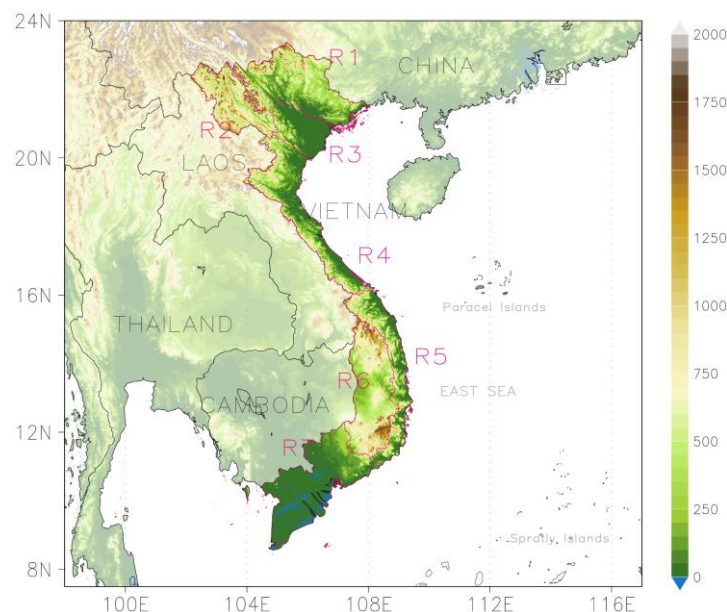


Fig. 1. Sub-climatic regions of Vietnam overlaid on the Hydroshed topographic map (elevation in meters)

2.2. Meteorological Data and Scenario

In this study, we investigate historical and projected drought conditions in Vietnam utilizing near-surface temperature (T2m), maximum/minimum daily temperature (Tmax/Tmin), and precipitation data (Pr) from the CMIP6-VN dataset, which comprises information from 35 downscaled CMIP6 GCMs (Tran-

Anh et al., 2023). The CMIP6-VN dataset represents a high-resolution climate projection dataset specifically developed for Vietnam's mainland territory through the Bias Correction and Spatial Downscaling (BCSD) method. Within the BCSD framework, quantile mapping was applied to correct biases in both temperature and precipitation data, ensuring alignment with observed climatological distributions while preserving the statistical relationships between large-scale climate patterns and local meteorological variables. This approach effectively addresses the coarse spatial resolution limitations of global CMIP6 models, achieving a refined $0.1^\circ \times 0.1^\circ$ (~ 10 km) resolution suitable for Vietnam's diverse topographic and monsoon-driven climatic conditions (Tran-Anh et al., 2022; Tran et al., 2024; Hung et al., 2024). The CMIP6-VN dataset has been thoroughly validated against 157 temperature and 481 precipitation observations from ground-based meteorological stations across Vietnam, exhibiting minimal biases in both temporal and spatial distributions of temperature and precipitation. Details on the validation process and performance metrics can be found in Tran-Anh et al. (2023). This ensemble, drawn from diverse modeling centers, incorporates varied representations of climate system processes, ensuring robust uncertainty quantification and enhanced reliability of projected drought characteristics across Vietnam's climatic regions.

Tab. 1. List of 22 CMIP6-VN models considered in this study

No.	Model Name	Original resolution	Development Institution	Country
1	ACCESS-CM2	$1.25^\circ \times 1.875^\circ$	CSIRO and Bureau of Meteorology	Australia
2	ACCESS-ESM1-5	$1.25^\circ \times 1.875^\circ$	CSIRO and Bureau of Meteorology	Australia
3	AWI-CM-1-1-MR	$0.94^\circ \times 0.94^\circ$	Alfred Wegener Institut	Germany
4	BCC-CSM2-MR	$1.125^\circ \times 1.125^\circ$	Beijing Climate Center, China Meteorological Administration	China
5	CMCC-ESM2	$1.0^\circ \times 1.0^\circ$	Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC)	Italia
6	CNRM-CM6-1-HR	$0.5^\circ \times 0.5^\circ$	Centre National de Recherches Météorologiques, Météo-France, and CNRS	France
7	CNRM-ESM2-1	$1.4^\circ \times 1.4^\circ$	Centre National de Recherches Météorologiques, Météo-France, and CNRS	France
8	CanESM5	$2.8^\circ \times 2.8^\circ$	Canadian Centre for Climate Modelling and Analysis	Canada
9	EC-Earth3-Veg	$0.7^\circ \times 0.7^\circ$	EC-Earth Consortium (multiple European institutions)	European
10	EC-Earth3	$0.7^\circ \times 0.7^\circ$	EC-Earth Consortium (multiple European institutions)	European
11	FGOALS-g3	$2.0^\circ \times 2.3^\circ$	Institute of Atmospheric Physics, Chinese Academy of Sciences	China
12	GFDL-ESM4	$1.0^\circ \times 1.25^\circ$	NOAA Geophysical Fluid Dynamics Laboratory	USA
13	GISS-E2-1-G	$2.0^\circ \times 2.5^\circ$	NASA Goddard Institute for Space Studies	USA
14	HadGEM3-GC31-LL	$1.25^\circ \times 1.875^\circ$	Met Office Hadley Centre	UK
15	INM-CM5-0	$1.5^\circ \times 2.0^\circ$	Institute of Numerical Mathematics, Russian Academy of Sciences	Russia
16	IPSL-CM6A-LR	$1.3^\circ \times 2.5^\circ$	Institut Pierre-Simon Laplace	France
17	MIROC-ES2L	$2.8^\circ \times 2.8^\circ$	Japan Agency for Marine-Earth Science and Technology, University of Tokyo	Japan
18	MIROC6	$1.4^\circ \times 1.4^\circ$	Japan Agency for Marine-Earth Science and Technology, University of Tokyo	Japan
19	MPI-ESM1-2-HR	$0.94^\circ \times 0.94^\circ$	Max Planck Institute for Meteorology	Germany
20	MRI-ESM2-0	$1.125^\circ \times 1.125^\circ$	Meteorological Research Institute, Japan Meteorological Agency	Japan

No.	Model Name	Original resolution	Development Institution	Country
21	NESM3	$1.875^{\circ} \times 1.875^{\circ}$	Nanjing University of Information Science and Technology	China
22	UKESM1-0-LL	$1.25^{\circ} \times 1.875^{\circ}$	Met Office Hadley Centre and Natural Environment Research Council	UK

We establish our analytical framework using historical simulations from 1985–2014 as the reference baseline, following the World Meteorological Organization's standard 30-year climatological period. Climate projections are analyzed across three periods: near-future (2015–2039), mid-future (2040–2069), and far-future (2070–2099). The 25-year near-future period aligns with standard climate assessment timelines while providing policy-relevant projections and maintaining sufficient length for robust statistical analysis.

This study examines three representative SSPs that span the range of plausible future emission trajectories: SSP1-2.6 (Sustainability pathway), SSP2-4.5 (Middle of the Road pathway), and SSP5-8.5 (Fossil-fueled Development pathway) (IPCC, 2023). SSPs are narratives outlining socioeconomic futures based on population, economic, technological, and climate policy assumptions (Riahi et al., 2017). The numerical suffix (2.6, 4.5, 8.5) denotes radiative forcing in W/m^2 by 2100, reflecting additional energy in the climate system from emissions. SSP1-2.6 (2.6 W/m^2) assumes strong mitigation and renewable energy adoption. SSP2-4.5 (4.5 W/m^2) reflects moderate mitigation with current trends. SSP5-8.5 (8.5 W/m^2) represents high emissions with minimal mitigation. These scenarios span a wide range of climate forcing, enabling robust assessment of drought trends under diverse socioeconomic and policy conditions.

2.3. Drought analysis

2.3.1. Standardized Precipitation Evapotranspiration Index

Drought assessment in this study employs the SPEI, a robust meteorological drought indicator that incorporates both precipitation and PET to provide comprehensive water balance representation (Vicente-Serrano et al., 2010). Unlike precipitation-only indices, SPEI accounts for temperature-driven evaporative demand, making it particularly suitable for climate change studies where rising temperatures significantly influence drought dynamics.

SPEI computation utilizes the established methodology involving probability distribution fitting to climatic water balance time series followed by standardization to a normal distribution. The analysis employs the SPEI R package (<https://cran.r-project.org/web/packages/SPEI/>), which provides validated implementation of the original algorithm and facilitates integration with statistical workflows. The detailed methodology for SPEI calculation can be found in the original work of Vicente-Serrano et al. (2010). Given Vietnam's agricultural vulnerability to short-term moisture deficits, we calculate SPEI using the one-month timescale as the primary indicator for capturing immediate drought impacts on crop development and water resources.

2.3.2. Potential Evapotranspiration Estimation

Since PET data are not directly available in the CMIP6-VN dataset, we employ the Hargreaves-Samani method (Hargreaves and Samani, 1985), which estimates PET using temperature and solar radiation data:

$$\text{PET} = 0.0023 \cdot (T_{\text{mean}} + 17.78) \cdot \sqrt{T_{\text{max}} - T_{\text{min}}} \cdot R_s \quad (1)$$

where PET represents potential evapotranspiration (mm/day), $\alpha = 0.0023$ is the empirical coefficient, T_{mean} , T_{max} , and T_{min} denote mean, maximum, and minimum daily temperatures ($^{\circ}\text{C}$), respectively, and R_s represents solar radiation ($\text{MJ/m}^2/\text{day}$) calculated as a function of latitude. This method provides reliable PET estimates for large-scale climate studies and has been extensively validated in tropical and subtropical regions similar to Vietnam's climate conditions.

2.3.3. Drought Characteristics and Trend Analysis

We analyze three primary drought characteristics: intensity (mean SPEI during drought episodes), frequency (number of drought events per period), and severity (average duration of drought events in months). Drought events are defined as consecutive months with $\text{SPEI} \leq -0.5$, employs the dry and wet categories as used in Tab. 2 (Li et al., 2015)

Temporal trend analysis employs the Mann-Kendall test, a non-parametric statistical method for detecting monotonic trends in hydroclimatic time series (Kendall, 1945). This approach requires no

assumptions about data distribution and provides robust trend detection in the presence of outliers and non-normal data characteristics common in climate variables. The test yields Kendall's tau coefficient indicating trend direction and magnitude, with statistical significance assessed at $p < 0.05$. Spatial consistency of trends across the model ensemble is evaluated using signal-to-noise ratios to identify regions with robust climate change signals relative to natural variability.

Tab. 2. SPEI drought index categories.

Moisture Category	SPEI
Extremely wet (EW)	2.00 and above
Very wet (VW)	1.50 to 1.99
Moderately wet (MW)	1.00 to 1.49
Near normal (NN)	−0.99 to 0.99
Moderately dry (MD)	−1.00 to −1.49
Severely dry (SD)	−1.50 to −1.99
Extremely dry (ED)	−2.00 and less

2.3.4. Uncertainty of Model Projections

Model projection uncertainty is quantified using the Signal-to-Noise Ratio (SNR) method (Li and Zhou, 2010), which evaluates climate change signal robustness relative to inter-model variability. The SNR is calculated as:

$$SNR = \frac{Signal}{Noise} \quad (2)$$

$$Signal = MME = \left| \frac{1}{n} (\sum x_i) \right| \quad (3)$$

$$Noise = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - MME)^2} \quad (4)$$

where x_i represents the projected change for pathway i , MME is the multi-model ensemble mean, and total models. $SNR > 1$ indicates robust climate signals with high confidence, while $SNR < 1$ reflects high uncertainty where model disagreement exceeds projected change magnitude.

3. Results and Discussion

3.1. Projection of Temperature and Precipitation

Fig 2 presents projected mean temperature increases across Vietnam and its climatic sub-regions through 2100, derived from the CMIP6-VN model ensemble. All regions demonstrate consistent warming trends under each emission scenario examined. The ensemble exhibits strong agreement with observed temperature data during the reference period (1985–2014), demonstrating minimal bias and high model fidelity. Relative to the baseline period, the SSP5-8.5 high-emission scenario projects the most substantial temperature increases, with national averages rising 4.5°C by century's end. The SSP2-4.5 scenario yields moderate warming of approximately 2.6°C, while SSP1-2.6 produces the smallest increases at 1.4°C. Under SSP1-2.6, which represents aggressive global climate mitigation efforts, temperatures stabilize at approximately 1.4°C above baseline throughout the latter half of the century. Scenario-dependent temperature divergence becomes pronounced after mid-century, with minimal differentiation evident in earlier decades. Northern Vietnam (regions R1–R4) exhibits enhanced warming relative to southern regions (R5–R7). By century end, region R1 is projected to experience 5.1°C warming compared to 4.0°C in region R7, indicating attenuated warming rates at lower latitudes. Model uncertainty remains consistently low throughout the historical period but increases substantially in future projections, with maximum uncertainty occurring toward century's end.

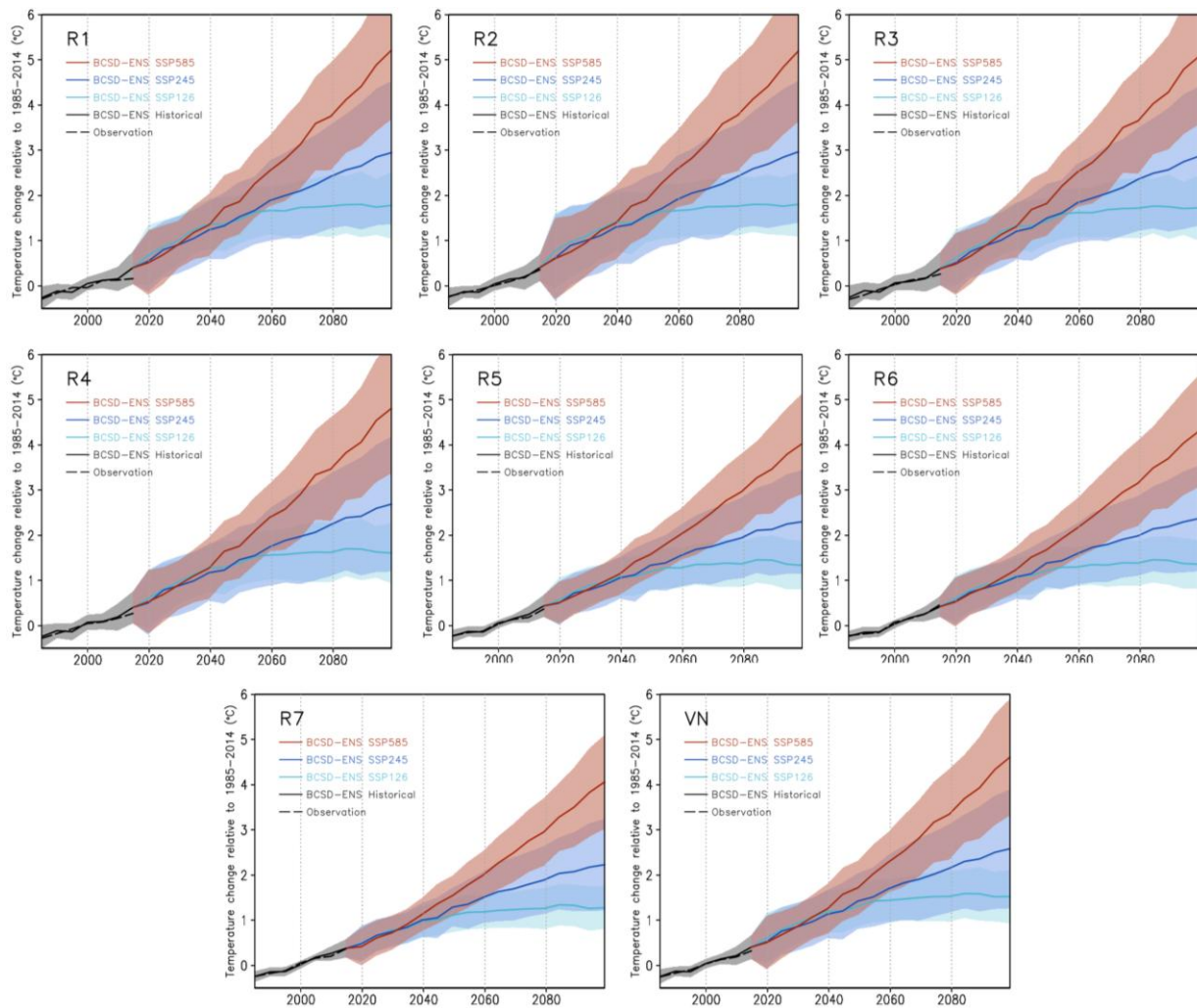


Fig. 2. Evolution of temperature anomaly in for Vietnam and the seven sub-climatic region during the reference period (1985–2014) and projections (2015–2099) based on the CMIP6-VN model ensemble. 10-year moving average was applied. The solid lines represent ensemble mean temperatures for the historical period (black), SSP1-2.6 (light blue), SSP2-4.5 (blue), and SSP5-8.5 (red). The dashed black line shows observed temperature data. Shaded areas indicate model uncertainty, represented by ± 1 standard deviation.

Figure 3 depicts projected precipitation anomalies relative to the reference period (1985–2014). The CMIP6-VN model ensemble projects general precipitation increases across all regions by the late 21st century, consistent with rising global mean temperatures. The ensemble demonstrates strong correspondence with historical observations, exhibiting minimal bias and consistent trends during the reference period. Precipitation increases exhibit lower magnitude and reduced signal clarity compared to temperature projections. The SSP2-4.5 scenario yields the largest precipitation increases, followed by SSP5-8.5, while SSP1-2.6 produces the smallest increases, particularly during the late century. For the period 2070–2099, SSP2-4.5 projects mean increases of 7.2% relative to baseline, compared to 5.4% under SSP5-8.5 and 3.2% under SSP1-2.6. Spatial precipitation patterns do not demonstrate clear correspondence with global warming magnitudes across scenarios. Additionally, no systematic regional precipitation gradients emerge among Vietnam's climatic sub-zones. Model uncertainty in precipitation projections substantially exceeds that of temperature, with historical period variations constrained to $\pm 10\%$ expanding to approximately $\pm 20\%$ during 2015–2099, with uncertainty remaining elevated throughout the projection period. These findings highlight the substantial uncertainty and spatiotemporal inconsistency inherent in precipitation projections, contrasting markedly with the robust and coherent temperature trends observed across scenarios and regions.

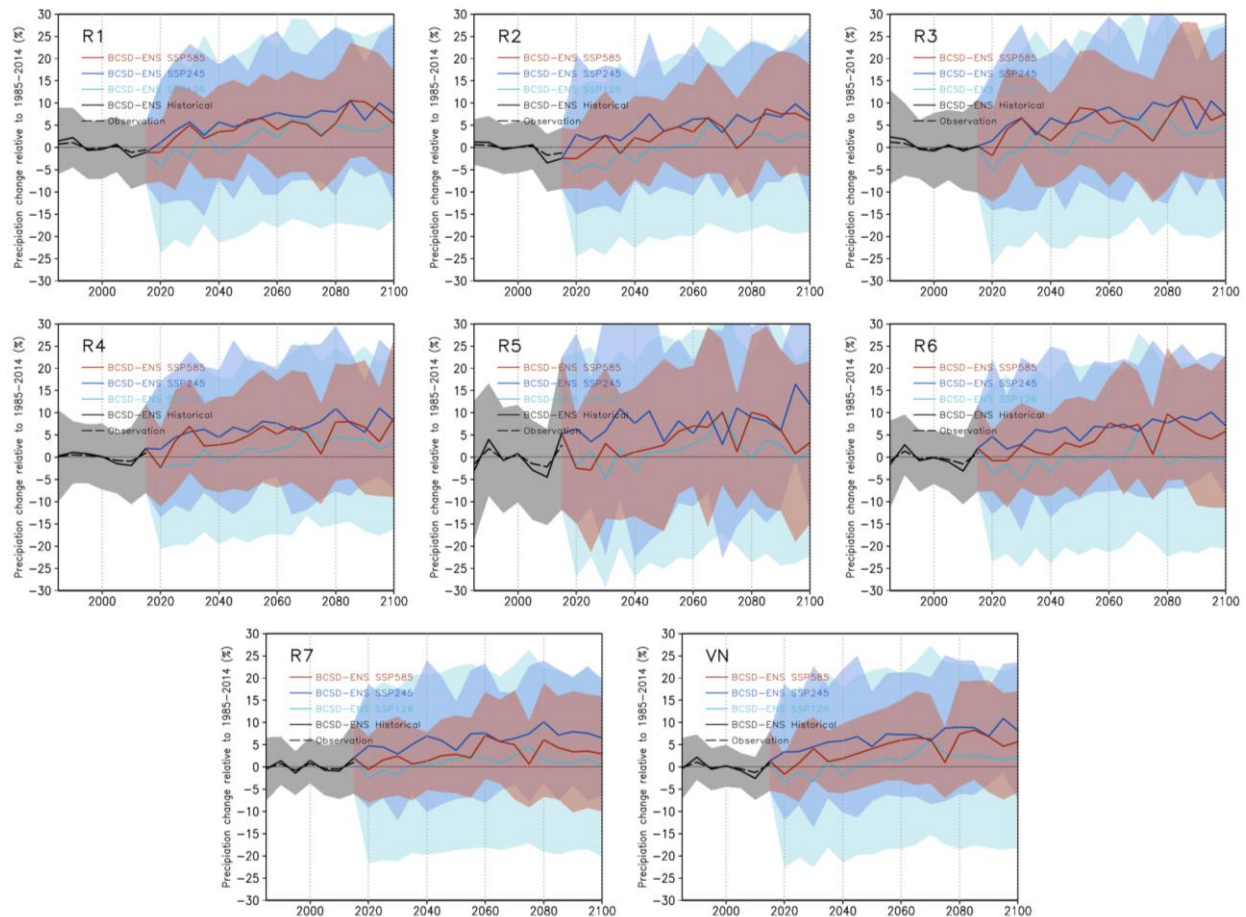


Fig. 3. Same with Fig. 2 but for precipitation.

3.2. Future Trends of Drought

Figure 4 presents the temporal evolution of one-month SPEI across Vietnam's seven climatic sub-regions (R1–R7) using the CMIP6-VN model ensemble for 1985–2099. The analysis reveals dynamic hydroclimatic variability characterized by alternating wet and dry phases, with declining SPEI during the reference period (1985–2014) followed by gradual recovery toward century's end. Historical dry conditions simulated by the ensemble align with documented drought events across Vietnam, including those reported for the Mekong Delta (Phan et al., 2020), national-scale meteorological droughts during 1961–2007 (Vu-Thanh et al., 2014), and multi-regional drought evolution during 1980–2017 (Stojanovic et al., 2020). These conditions reflect moderate drought intensity ($\text{SPEI} < -0.5$), driven by significantly temperature increases compared to the slightly increasing in precipitation. Compared to CMIP5-based studies, which reported similar drying trends but underestimated southern Vietnam's drought intensity (Nguyen-Ngoc-Bich et al., 2021), CMIP6-VN's higher resolution better captures local monsoon variability. Near-term projections (2015–2039) indicate continued SPEI decline across all scenarios, with SSP1-2.6 exhibiting the most pronounced drying, characterized by extended drought episodes of moderate intensity persisting across multiple consecutive years. Conversely, SSP2-4.5 and SSP5-8.5 scenarios project shorter, less intensive dry periods during this timeframe. Mid-century projections (2040–2069) demonstrate a distinct hydroclimatic transition, with SPEI exhibiting clear upward trends and a notable shift from dry to wet conditions. This transition is most pronounced under SSP1-2.6, where wet conditions become predominant. Similar wetting trends emerge under SSP2-4.5 and SSP5-8.5, though with reduced magnitude. Late-century projections (2070–2099) indicate modest SPEI increases (+0.1 to +0.3), with northern regions (R1–R3) showing stronger wetting ($\text{SPEI} = +0.3$ to +0.6, 10–15% precipitation increase) than southern regions (R6, R7), where balanced wet-dry cycles persist under SSP2-4.5 and SSP5-8.5. This latitudinal contrast, not fully captured in CMIP5 studies (Muangthong et al., 2020), highlights CMIP6-VN's ability to resolve regional nonlinearities driven by monsoon dynamics and topography.

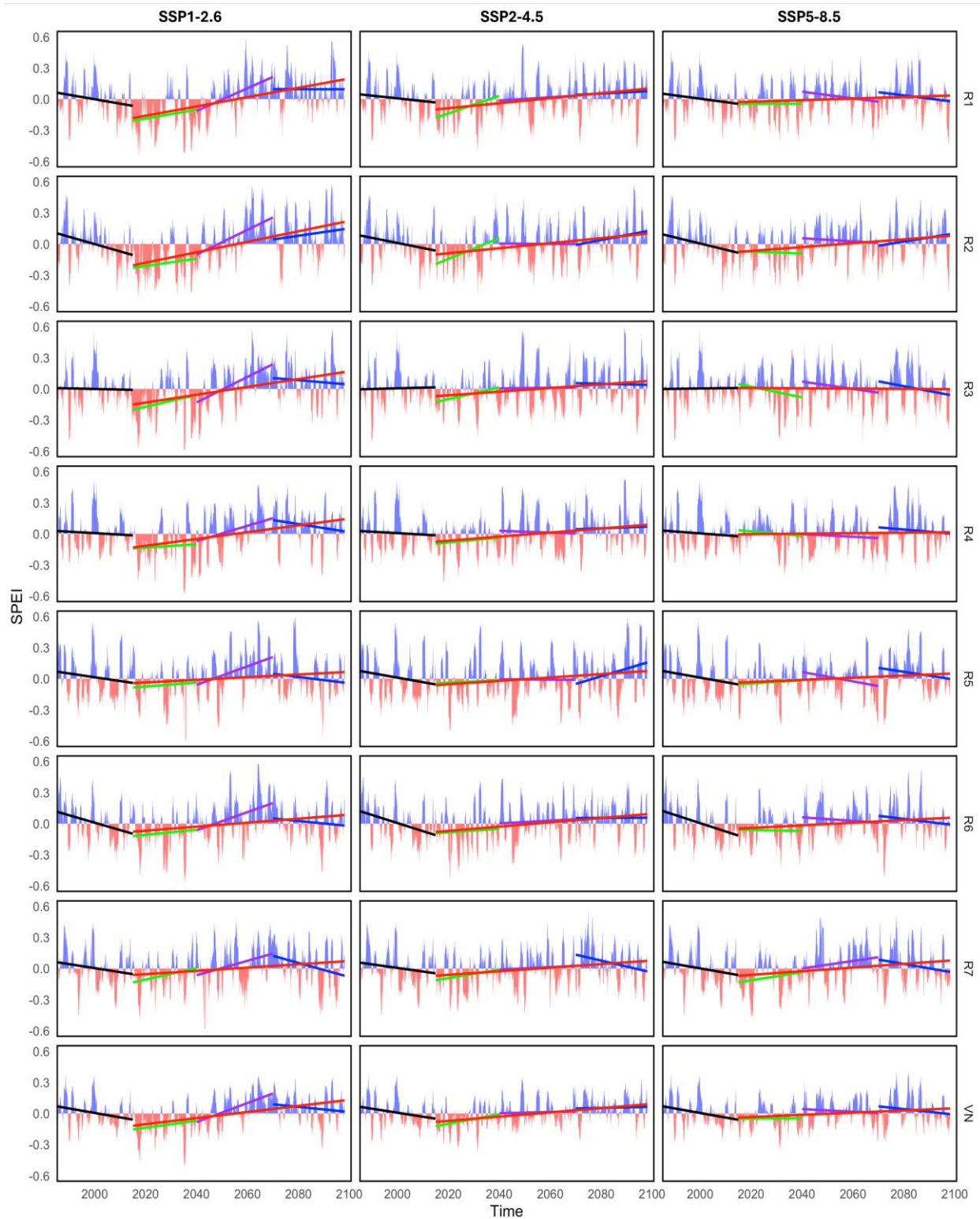


Fig. 4. Changes in the monthly SPEI index for Vietnam and its seven sub-climatic regions from 1985 to 2099 under three scenarios: SSP1-2.6 (left), SSP2-4.5 (middle), and SSP5-8.5 (right). Positive SPEI values are shown in blue, while negative values are shown in red. Trend lines are indicated for the historical period (1985–2014) in black, near future (2015–2039) in green, mid-century (2040–2069) in purple, far future (2070–2099) in blue, and the full projection period (2015–2099) in red.

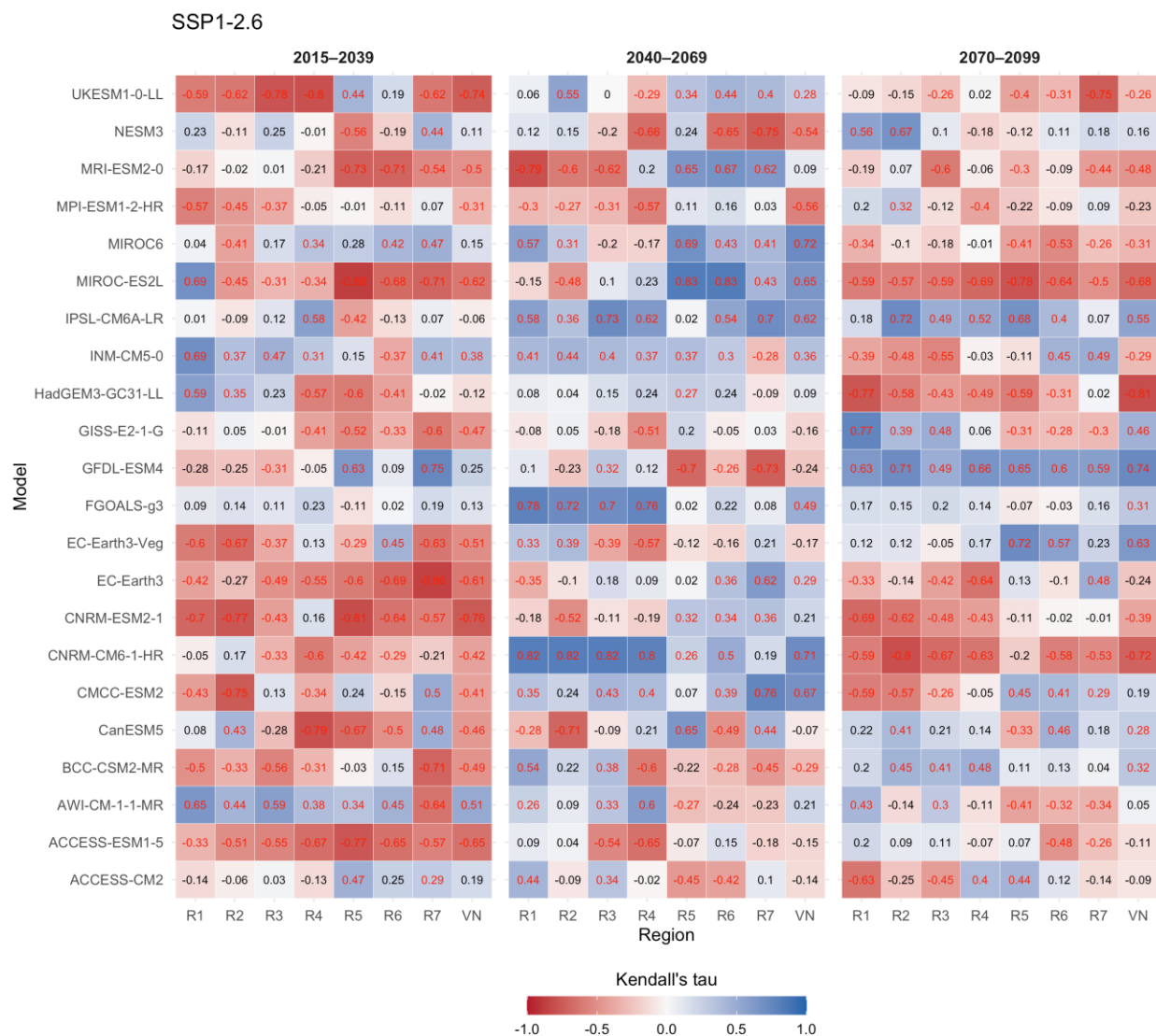


Fig. 5. Heatmap of Kendall's tau values for CMIP6-VN models across Vietnam's seven sub-climatic regions under SSP1-2.6 for the near future (2015–2039), mid-century (2040–2069), and far future (2070–2099). Blue grid cells indicate positive trends, while red cells indicate negative trends. Statistically significant trends (p -value < 0.05) are marked with red text.

Mann-Kendall trend analysis of SPEI projections across CMIP6-VN models under SSP1-2.6 is shown in Figure 5. Near-future projections (2015–2039) show predominantly negative Kendall's tau values, with most models indicating statistically significant drying ($p < 0.05$). Model consensus is strongest in regions R2, R4, R5 (15/22 models) and R1, R6 (14/22 models), with lowest agreement in R3, R7 (12/22 models), indicating differential regional sensitivity to low-emission forcing. Mid-future projections (2040–2069) demonstrate hydroclimatic transition, with 13/22 models showing positive tau values with 9 of those exhibiting significant wetting trends. This temporal shift reflects delayed hydrological response to stabilized radiative forcing. Far-future projections (2070–2099) exhibit reduced consensus between models, characterized by balanced positive and negative trends, suggesting potential hydroclimatic instability as the system approaches equilibrium under sustained low greenhouse gas concentrations.

Figure 6 demonstrates that SSP2-4.5 exhibits similar temporal SPEI patterns to SSP1-2.6 but with reduced magnitude. Near-future drying occurs in 13/22 models (9 significant), mid-future wetting in 12/22 models (7 significant), and mixed late-century projections. Both SSP1-2.6 and SSP2-4.5 exhibit substantial inter-model variability, with some models projecting consistent wet or dry conditions across all regions in a period. Fig 7 reveals maximum inter-model uncertainty under SSP5-8.5, with nearly equal numbers of models projecting significant increasing versus decreasing SPEI trends: 7 decrease/8 increase (2015–2039), 9 decrease/8 increase (2040–2069), and 6 decrease/11 increase (2070–2099). Inter-model divergence increases with emission intensity due to amplified temperature-evapotranspiration-precipitation feedbacks.

Under high-emission scenarios, enhanced warming accelerates evapotranspiration, potentially offsetting precipitation increases and creating complex patterns that challenge model representation. Intensified convective processes may exceed current model parametric limits, producing divergent projections. This scenario-dependent uncertainty pattern demonstrates that while low-emission pathways (SSP1-2.6) produce consistent temporal transitions despite magnitude variations, high-emission scenarios (SSP5-8.5) trigger competing hydrological processes with fundamentally different model representations. The nonlinear increase in SPEI uncertainty contrasts sharply with robust temperature projections, highlighting amplified risks of unmitigated climate change for regional hydroclimatic predictability.

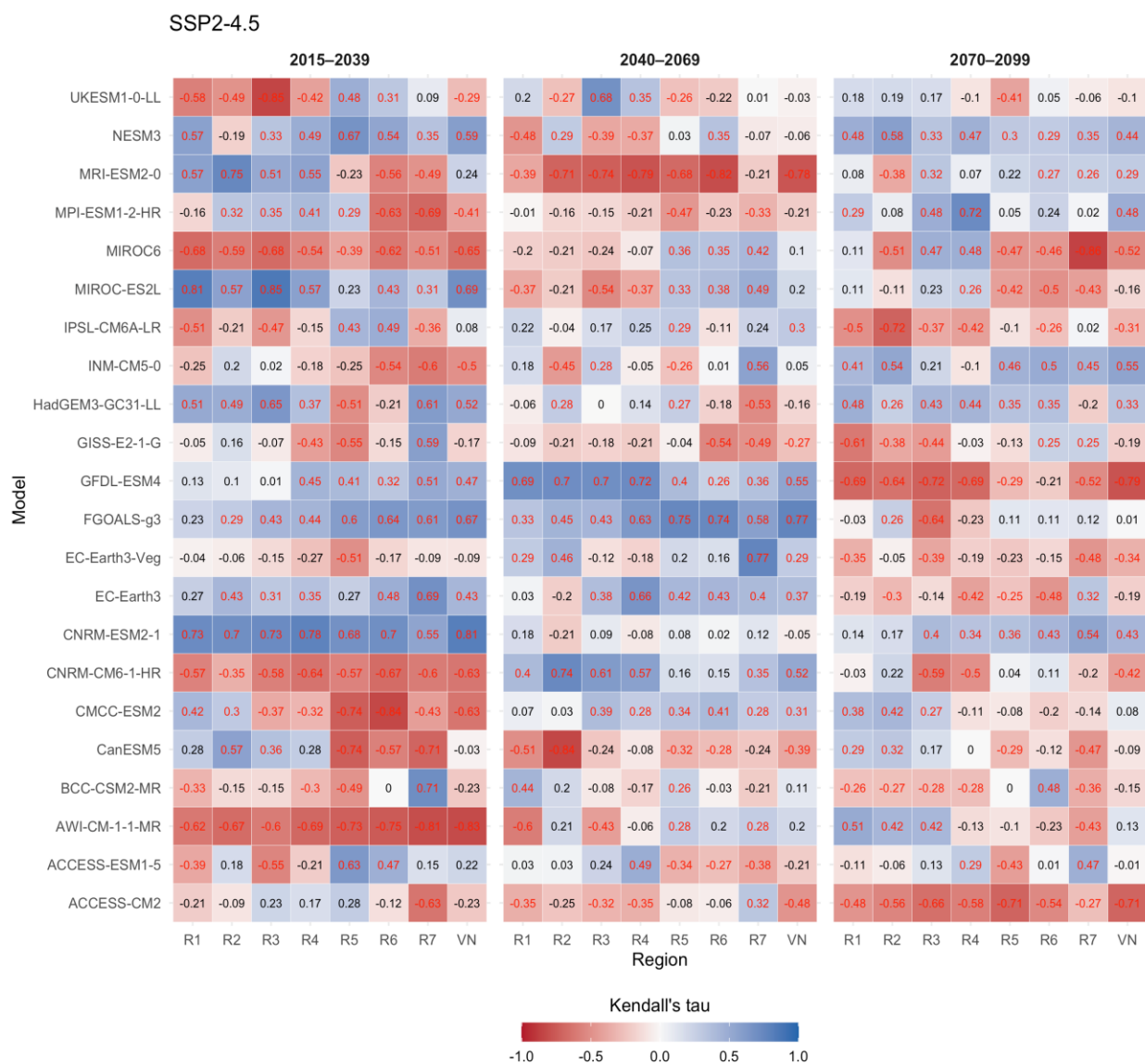


Fig. 6. Similar to Figure 5. But for SSP2-4.5

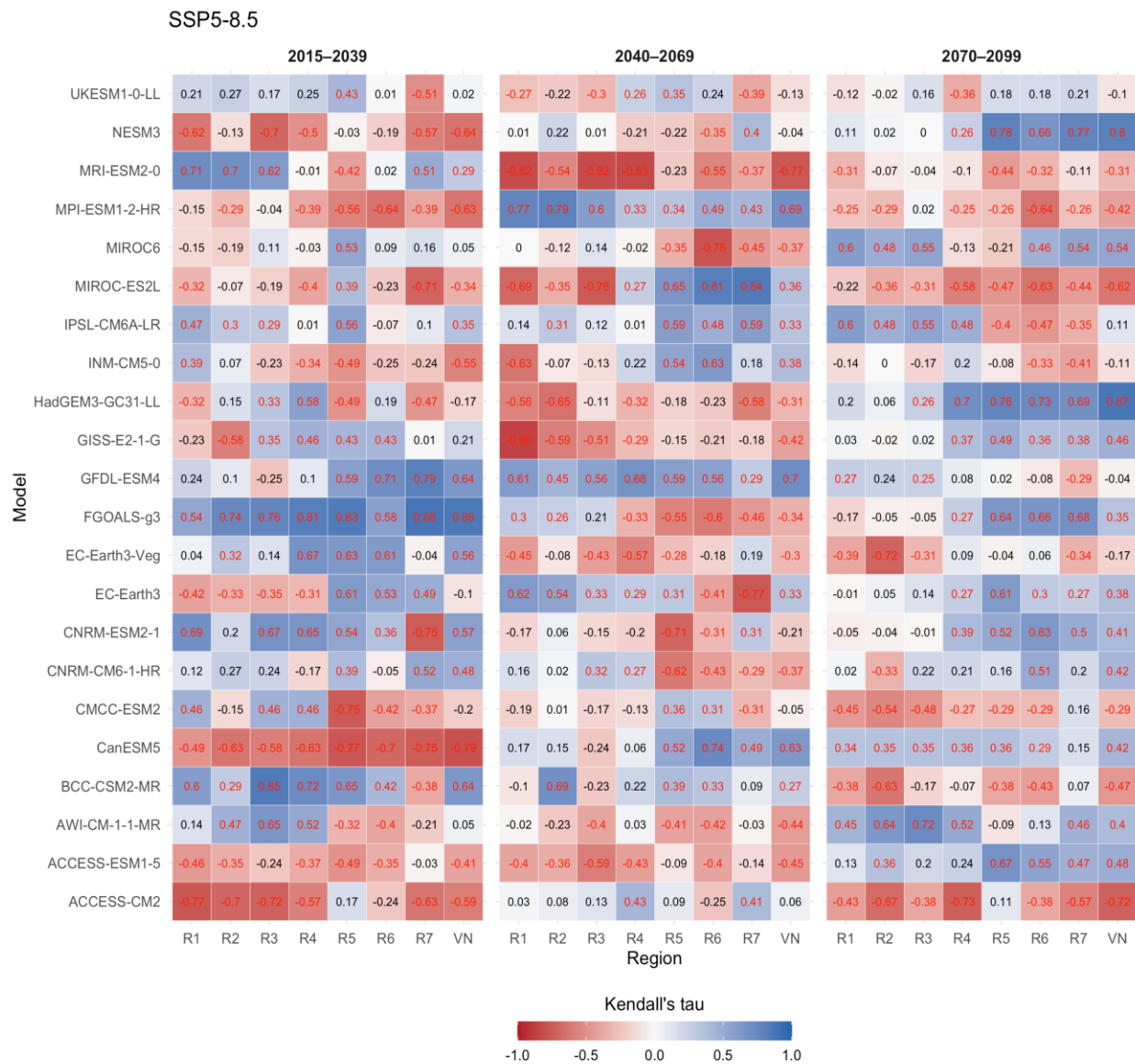


Fig. 7. Similar to Figure 5. But for SSP5-8.5

3.3. Spatial Distribution of Drought Intensity, Frequency and Severity

The spatial distribution of drought intensity, based on mean SPEI values during drought episodes across periods and scenarios, is shown in Figure 8. For the baseline period (1985–2014), the national average SPEI during droughts is -1.1 (range: -1.14 to -1.10), indicating moderate severity. Central and southern regions (R4, R6, R7) exhibit SPEI values as low as -1.3, underscoring established regional vulnerabilities. Under SSP1-2.6, drought intensity increases by 19.1% in the near future (2015–2039, SPEI = -1.31), with central Vietnam (R1, R4) experiencing the strongest intensification (SPEI = -1.5). By mid-century (2040–2069), intensity decreases by 15.3% (SPEI = -1.11) relative to the near future, followed by a slight further reduction to -1.08 by late century (2070–2099), representing a 1.8% improvement compared with the baseline. Model consensus (signal-to-noise ratio, SNR > 1) is strong for increased drought severity in regions R1, R3, R4, and R5, though agreement weakens toward late century, reflecting complex regional responses under stabilized radiative forcing. Under SSP2-4.5, near-future drought intensity rises by 22.7% in southern Vietnam (R6, R7, SPEI = -1.35). This increase is primarily driven by elevated near-surface temperature (+0.74°C) despite precipitation being projected to increase (+4.3% above baseline). Mid- and late-century patterns indicate a northward shift in drought severity, with intensity increases of 10–12% in northern regions (R2, R3, SPEI = -1.22), contrasting with relatively stable southern areas. Under SSP5-8.5, near-term changes remain ambiguous due to nonlinear precipitation–evapotranspiration interactions, with precipitation projected to increase by 2.3% while temperature rises by 0.71°C. Consequently, differences between scenarios are minimal in the near future, as the effects of moderate warming and modest precipitation gains offset each other. However, by late century, SSP5-8.5 projects a marked intensification

in northern Vietnam, with SPEI values comparable to those under SSP2-4.5 (around -1.22), while southern regions remain relatively unchanged. Across scenarios, results suggest increasing drought severity in northern and central Vietnam under intermediate- and high-emission pathways, whereas southern Vietnam shows signs of stabilization or even slight relief by late century. Model consensus weakens under higher-emission scenarios ($\text{SNR} < 0.8$), indicating greater uncertainty in simulating the balance between temperature-driven evapotranspiration and precipitation changes.

Drought frequency, shown in Figure 9, exhibits non-monotonic trends under SSP1-2.6, decreasing from 17.1 events (1985–2014) to 8.4 events (2015–2039, or 10.1 events per 30 years, a 40.9% reduction), then rising to 17.7 events (2040–2069, 3.5% increase from baseline) and 22.2 events (2070–2099, 29.8% increase). Southern regions (R6, R7) show the largest near-future reductions, with some areas dropping by 14.4 events (48% decrease on a 30-year scale), linked to temporary precipitation increases (5–8%). All scenarios project a national average increase of approximately 5 events (29.2%) by late century compared to baseline, consistent across SSPs. Compared to CMIP5-based studies, which projected 10–20% frequency increases in southern Vietnam (Nguyen-Ngoc-Bich et al., 2021), our CMIP6-VN results show higher increases (25–30%) in northern regions (R2, R3), possibly due to improved resolution capturing local monsoon dynamics. Model consensus is strong for near-future decreases ($\text{SNR} > 1.2$) but weakens mid-century ($\text{SNR} \approx 0.7$), indicating uncertainties in drought regime shifts, particularly in northern Vietnam where precipitation variability increases by 10–15%.

Figure 10 illustrates drought severity projections (duration in months/event) across scenarios and future periods. Nationally, severity increases from a baseline of 7.6 months/event (1985–2014) to 8.6 months/event (SSP5-8.5, 13.2% increase) and 9.4 months/event (SSP1-2.6, 23.7% increase) during 2015–2039, driven by a near-surface temperature increase of 0.82°C above baseline, while precipitation remains nearly unchanged (within $\pm 1\%$). Mid-century projections (2040–2069) show reductions to 7.9 months/event (SSP2-4.5, SSP5-8.5, 3.9% increase) and 8.0 months/event (SSP1-2.6, 5.3% increase), followed by late-century values of 7.2 months/event (SSP1-2.6, 5.3% decrease) and 8.0 months/event (SSP5-8.5, 5.3% increase). Region R4 exhibits extreme severity, with durations reaching 12.3 months/event (SSP5-8.5, 61.8% increase) to 15.7 months/event (SSP2-4.5, 106.6% increase). These findings align with Do et al. (2024), who reported prolonged drought durations in central Vietnam using CMIP6, but our higher-resolution CMIP6-VN dataset reveals greater spatial variability in R4, capturing local topographic influences. Strong model consensus ($\text{SNR} > 1.5$) exists for near-future severity increases under SSP1-2.6 and SSP2-4.5 in central and southern regions (R4, R6, R7), but weakens under SSP5-8.5 ($\text{SNR} \approx 0.6$) and late-century across all scenarios, reflecting uncertainties in long-term drought persistence under high radiative forcing. Notably, changes in drought severity do not scale linearly with global warming trends, as projected precipitation increases (2–5% by 2070–2099 under SSP2-4.5 and SSP5-8.5) partially offset temperature-driven evapotranspiration rises. This decoupling highlights drought as a localized phenomenon in Vietnam, particularly in regions like R4, where monsoon-driven precipitation variability (10–15% increase in R2, R3) and complex topography amplify local drought severity over global trends. Nonlinear interactions, especially evapotranspiration outpacing precipitation changes, drive these patterns, with northern regions (R2, R3) showing higher sensitivity due to monsoon variability, consistent with regional findings by Nguyen-Ngoc-Bich et al. (2022).

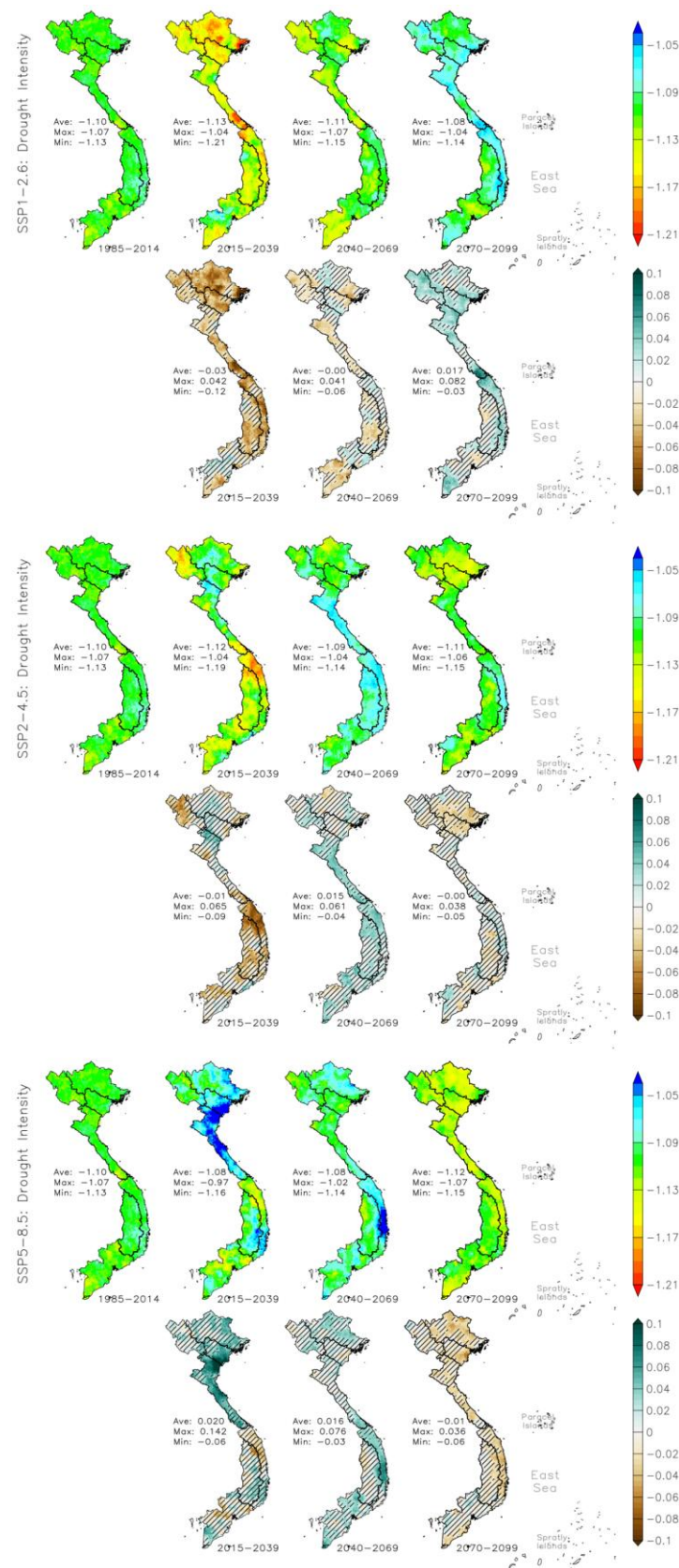


Fig. 8. Spatial patterns of projected changes in drought intensity over Vietnam for the near future (2015–2039), mid-century (2040–2069), and far future (2070–2099) based on the CMIP6-VN model ensemble under SSP1-2.6 (top panel), SSP2-4.5 (middle panel), and SSP5-8.5 (bottom panel). In each panel, the top row shows absolute projected drought intensity for each period, while the bottom row shows anomalies relative to the 1985–2014 baseline. Hatched areas indicate regions with a signal-to-noise ratio (SNR) < 1, reflecting low model agreement.

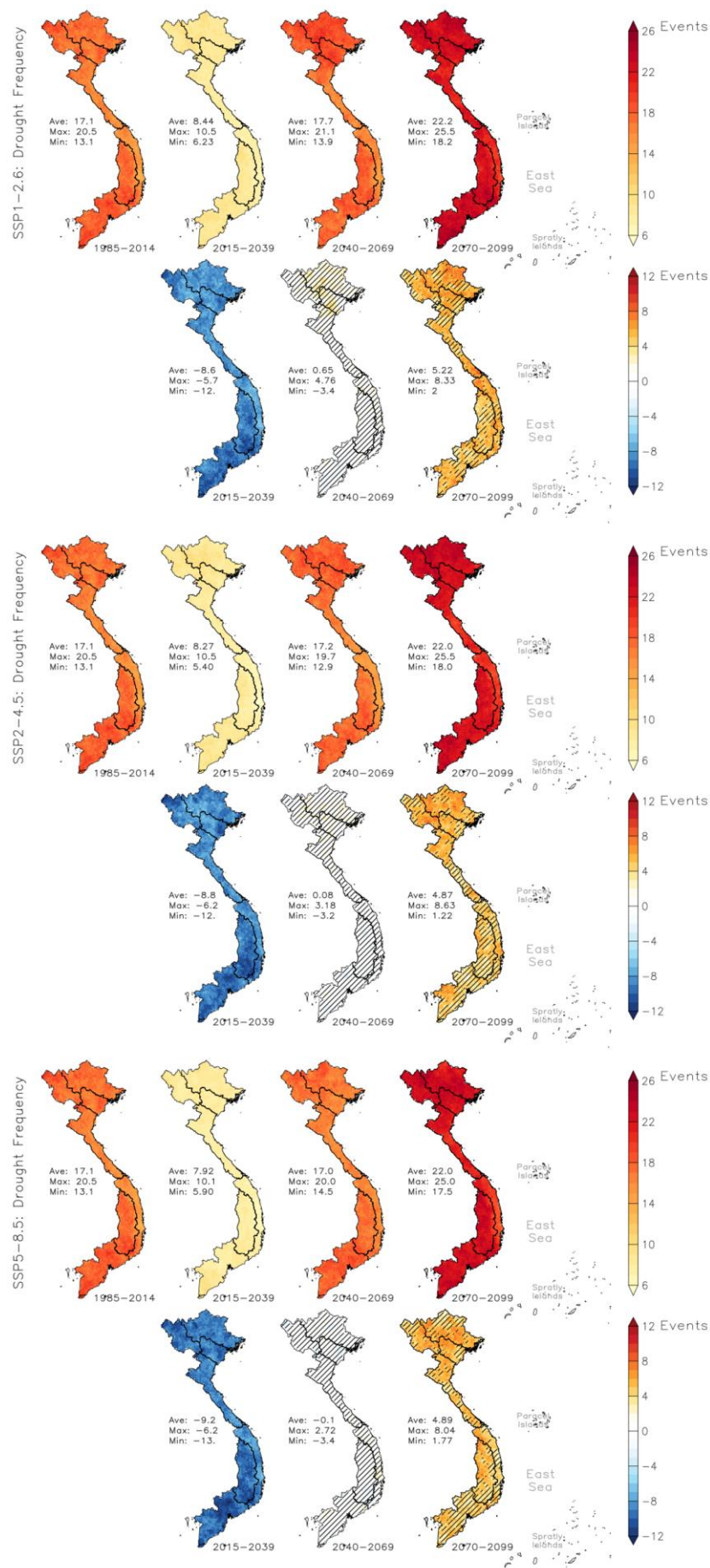


Fig. 9. Similar to Figure 8. But for drought frequency

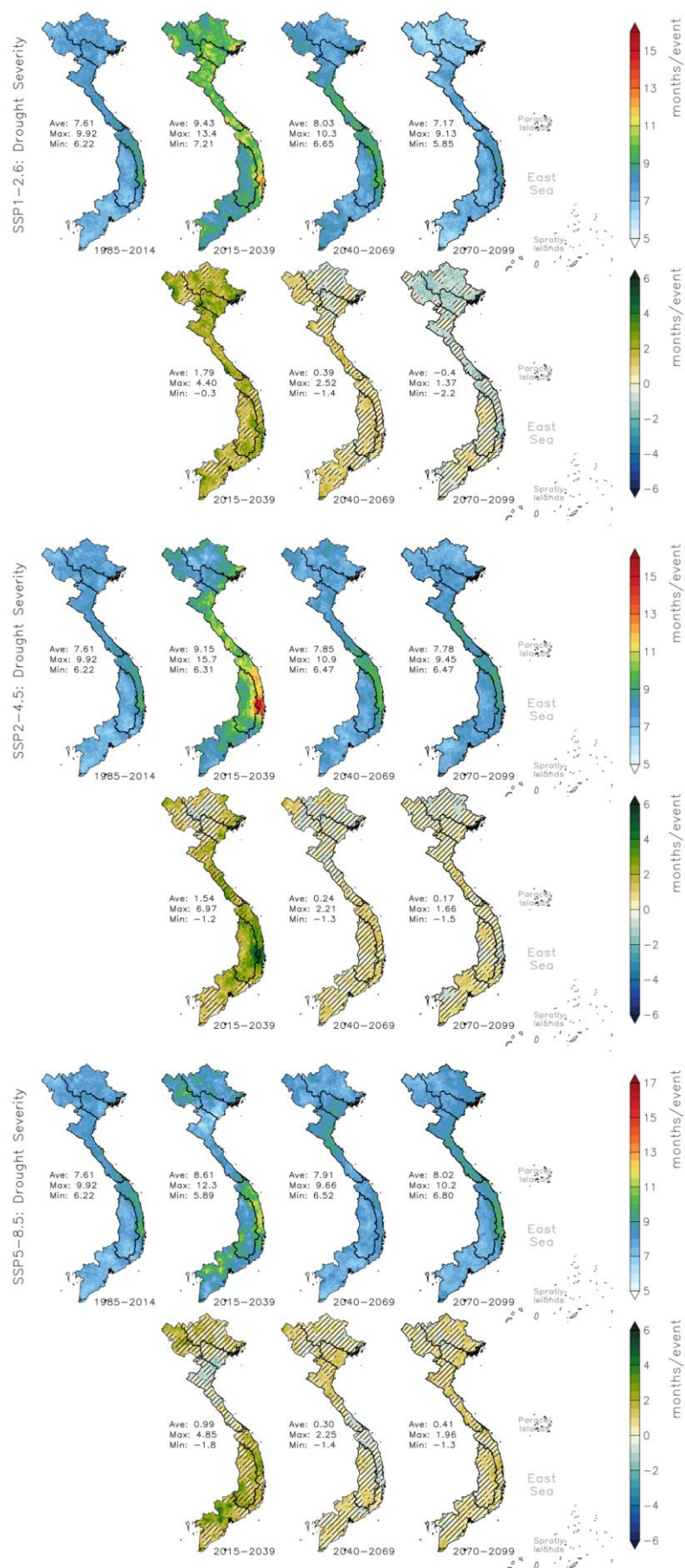


Fig. 10. Similar to Figure 8. But for drought severity

4. Conclusion

This study assessed future drought evolution across Vietnam's seven climatic sub-regions (R1–R7) using the one-month Standardized Precipitation Evapotranspiration Index (SPEI) derived from 22 CMIP6-VN downscaled models under three emission scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5) for 2015–2099. Leveraging the high-resolution (10-km) CMIP6-VN dataset, with potential evapotranspiration estimated via the Hargreaves-Samani method, we examined drought intensity, frequency, and severity through Mann-Kendall trend tests and spatial distribution assessments, capturing localized hydroclimatic dynamics driven by Vietnam's complex topography and monsoon climate.

The results confirm robust warming trends across all regions and scenarios, with temperature increases ranging from 1.4°C (SSP1-2.6) to 4.5°C (SSP5-8.5) by 2100. Northern regions (R1–R4) experience greater warming (up to 5.1°C in R1) than southern regions (4.0°C in R7). Precipitation is projected to increase modestly (3.2–7.2% by 2070–2099), with SSP2-4.5 showing the largest gains (7.2%), though uncertainties are higher than for temperature. Drought characteristics exhibit significant temporal and spatial variability. In the near future (2015–2039), drought frequency decreases (e.g., from 17.1 to 8.4 events under SSP1-2.6, a 40.9% reduction), but intensity (SPEI = -1.31, 19.1% increase) and severity (9.4 months/event, 23.7% increase) rise, driven by temperature increases (0.5–0.82°C) despite near-stable precipitation (± 1 –2%). Mid-century (2040–2069) shows a hydroclimatic transition, with 13/22 models under SSP1-2.6 indicating wetting trends (SPEI = +0.2 to +0.5) due to precipitation recovery (5–10%). Late-century projections (2070–2099) reveal renewed drought stress, with a national increase of ~5 events (29.2%) across all scenarios, though northern regions (R1–R3) exhibit stronger wetting (SPEI = +0.6) than southern regions (R6, R7), where wet-dry cycles persist. Central region R4 faces the most extreme severity, with drought durations reaching 15.7 months/event (106.6% increase) under SSP2-4.5, driven by significant temperature increase increases (1.2–3.8°C). In contrast, southern regions (R6, R7) show more resilience, particularly in reduced drought frequency, reflecting different climate sensitivities across Vietnam's latitudinal gradient. These patterns result from complex interactions between topography, monsoon dynamics, and emissions forcing. Model agreement is high in the near term, especially in R2, R4, and R5 (15/22 models under SSP1-2.6). However, uncertainty increases toward the end of the century and under high-emission scenarios. SSP5-8.5 shows the least agreement, with models nearly split on whether droughts will intensify or ease.

These findings highlight Vietnam's increasing drought challenges, with a shift toward fewer but more intense and prolonged events, particularly in central (R4) and northern (R1–R3) regions. The compensatory dynamics between frequency and severity, coupled with scenario-dependent uncertainties, underscore the critical need for robust mitigation (e.g., SSP1-2.6) to reduce long-term hydroclimatic unpredictability. The reliable near-future projections provide a foundation for targeted adaptation strategies, such as enhanced irrigation and water management, to bolster agricultural resilience and water security across Vietnam's diverse climatic zones.

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