

RESEARCH ARTICLE

Projected evolution of drought characteristics in Vietnam based on CORDEX-SEA downscaled CMIP5 data

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Abstract

In this study, the projected drought characteristics over Vietnam for the future periods of the middle (2046–2065) and end of the 21st century (2080–2099) were investigated under the Representative Concentration Pathway (RCP) scenarios RCP4.5 and RCP8.5. The drought characteristics (duration, severity, intensity, inter-arrival time, and geographic extent) were estimated based on the Palmer Drought Severity Index (PDSI). The PDSI was calculated using temperature and precipitation data from six regional climate downscaling experiments and their ensemble conducted by the Coordinated Regional Climate Downscaling Experiment-Southeast Asia (CORDEX-SEA) project. Projected changes of drought characteristics in the future periods were determined with respect to those in the baseline period 1986–2005. Results show biases in the regional climate model (RCM) outputs, namely an underestimation of temperature and an overestimation of precipitation, which also affect the representation of drought characteristics by overestimating the PDSI. In terms of projections, substantial increases of drought duration, severity and intensity, and decreases in the inter-arrival time are found over the Red River Delta, northern parts of the North Central sub-region, parts of the Central Highlands and over southern Vietnam. The droughts are projected to be more widespread under scenario RCP8.5 than RCP4.5, especially in southern Vietnam. With the increasing likelihood of droughts in Vietnam as a result of climate change, sustainable

water resources management should be taken into account for agriculture, natural ecosystems and social development.

KEYWORDS

CORDEX-SEA, drought, PDSI, RegCM, regional climate projection, Vietnam

1 | INTRODUCTION

Drought is one of the world's costliest natural disasters with significant impacts on various sectors and a large amount of the population every year (WMO, 2006). According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013), drought has substantially increased in different parts of the world due to global warming. Over the past decades, many studies applied global climate models (GCMs) to assess the impacts of climate change on drought conditions over different parts of the world (e.g., Kim and Byun, 2009; Dai, 2011b; Touma *et al.*, 2015). On a global scale, projections of GCMs showed that the aridity increases over southern Europe, the Middle East, and most of the regions of the Americas, Africa, Australia, and Southeast Asia in the 21st century (Dai, 2011b). Both the area and frequency of agricultural drought are projected to increase by 50–200% even under low to moderate emission scenarios (Zhao and Dai, 2017). Meteorological drought is expected to worsen in many regions, such as the Mediterranean, Central America, Brazil, South Africa, and Australia (Collins *et al.*, 2013). On a regional scale, the dry periods between two wet spells are projected to increase. For example, the dry conditions show a tendency to expand across the southwestern part of North America in spring and also to intensify in summer (Cook *et al.*, 2015; Swain and Hayhoe, 2015). Over the southeastern United States, droughts tend to become more severe in the future, especially during the summer season (Mitra *et al.*, 2018). Drought conditions are also expected to intensify under the Representative Concentration Pathway (RCP) RCP8.5 scenario in southern European cities (Guerreiro *et al.*, 2018). Ahmadalipour and Moradkhani (2018) indicated that most of the southern and northern African countries are becoming more vulnerable to drought. In China, drought risk is projected to increase, especially in the eastern part of the country (Wang and Chen, 2014; Chen and Sun, 2017). Over South Korea, persistent short-term drought is likely to increase in the future (Rhee and Cho, 2016).

State-of-the-art GCMs provide the future state of the atmosphere with an average spatial resolution of more than 100 km. These simulations are too coarse to accurately represent the fine-scale details that characterize

the regional climate, especially in areas with complex orography, heterogeneous land cover or at coastlines (Giorgi, 2019). To assess local climate variables, in particular the evolution of drought at a finer scale, regional climate models (RCMs) have been widely used (e.g., Sushama *et al.*, 2010; PaiMazumder *et al.*, 2013; Spinoni *et al.*, 2020). Sushama *et al.* (2010) projected the changes in dry spell characteristics over the Canadian Prairies using the Canadian RCM (CRCM). Their results suggest an increase in the number of dry days for 10- and 30-year return periods of maximum dry spell duration for the 2041–2070 and 2071–2100 future periods. Several drought studies at the regional scale highlighted significant differences compared with the global scale (PaiMazumder *et al.*, 2013; Spinoni *et al.*, 2020). The analysis of future drought characteristics at the regional scale is fundamental in assessing the impact of climate change on local habitats. However, a challenge for using regional climate projections in impact assessments lies in the uncertainty in the representation of atmospheric processes in the GCMs and RCMs (Déqué *et al.*, 2007). Hence, an ensemble of simulations is often used to characterize and overcome the model uncertainty (Vu *et al.*, 2015a, 2015b; Masud *et al.*, 2017; Raghavan *et al.*, 2017).

To study the impacts of climate change over Southeast Asian (SEA), a prerequisite is to have high-resolution projection data. The Southeast Asia Regional Climate Downscaling/Coordinated Regional Climate Downscaling Experiment-Southeast Asia (SEACLID/CORDEX-SEA, hereafter referred to as CORDEX-SEA) project was established with such a purpose. The CORDEX-SEA project was funded by the Asia-Pacific Network (APN) for Global Change Research. Based on the CORDEX-SEA high-resolution multi-model simulations, several scientific papers have been published recently (e.g., Juneng *et al.*, 2016; Ngo-Duc *et al.*, 2017; Cruz *et al.*, 2017; Tangang *et al.*, 2019, 2020a,b; Nguyen-Thuy *et al.*, 2020; Supari *et al.*, 2020; Nguyen-Thi *et al.*, 2021). However, there has been no detailed study on the drought projections over the region.

Located in Southeast Asia, with a tropical monsoon climate and a coastline of more than 3,260 km, Vietnam is one of the most disaster-prone countries in the world (World Bank, 2010; Le *et al.*, 2019). Ranked third in

frequency after flood and typhoon, drought is one of the costliest natural disasters in Vietnam (World Bank, 2010). Drought has a wide range of impacts on the agricultural and water resources sectors in Vietnam. According to Sutton *et al.* (2019), severe droughts have affected most of the sub-regions in Vietnam including the Red River Delta, the South Central region, southern Vietnam and the Central Highlands since the 1997–1998 El Niño event. The 1997–1998 drought event affected about 120,000 ha of arable land with estimated losses of 445 million US dollars. The 2015–2016 drought was considered to be the strongest and longest drought in Vietnam in the past 90 years, which was attributed to the 2014–2016 El Niño event (UNDP, 2016). This event severely affected local people and agriculture in the Central Highlands, the South Central region and the Mekong River Delta (UNDP, 2016; Tran *et al.*, 2017; Nguyen *et al.*, 2019; Sutton *et al.*, 2019) along with 220,000 ha of arable land, resulting in the loss of about 674 million US dollars (Sutton *et al.*, 2019). There have been several studies conducted to examine the drought evolution in Vietnam (Vu-Thanh *et al.*, 2013; Vu *et al.*, 2015a, 2015b; Vu and Mishra, 2016; Vu *et al.*, 2018; Le *et al.*, 2019). However, these studies only evaluated the historical drought characteristics. For example, Le *et al.* (2019) used observed data from 131 meteorological stations to investigate the characteristics of droughts over Vietnam during the period 1980–2014 (35 years). They found an increasing trend in drought in the North, the South and Central Highlands, but a decreasing trend in the Central sub-regions. For future planning in agricultural adaptation and water resource management, it is crucial to understand the potential future changes in various drought characteristics.

The main objectives of this study are twofold: (a) to evaluate the ability of applying RCM model data to investigate spatial and temporal drought conditions using the Palmer Drought Severity Index (PDSI) over Vietnam; and (b) to evaluate projections of drought characteristics such as duration, severity, intensity, inter-arrival time and spatial extent, over the country under the RCP4.5 and RCP8.5 scenarios. Section 2 describes the study area, data and gives an outline of the methods. Section 3 presents the results. Conclusions are drawn in Section 4.

2 | STUDY AREA, DATA, AND METHODS

2.1 | Study area

Vietnam is a country in Southeast Asia. The mainland of Vietnam is approximately bounded by the latitudes 8 and

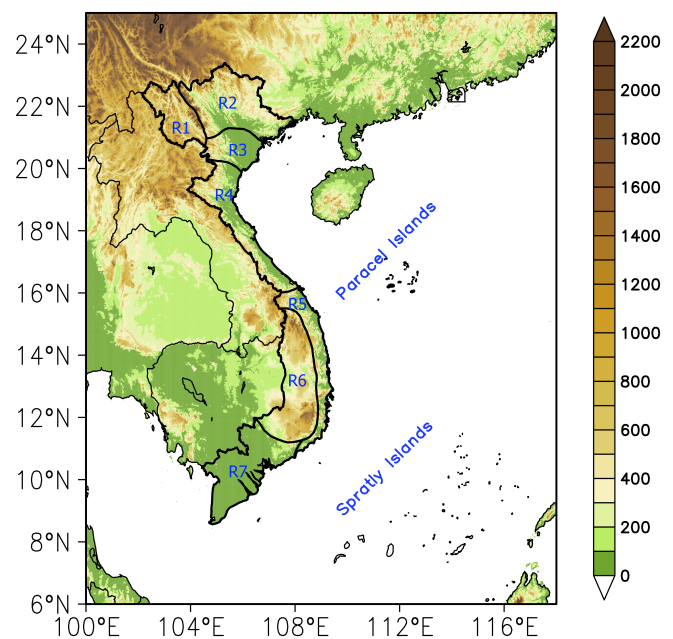


FIGURE 1 Vietnam and its seven climatic sub-regions (R1: Northwest, R2: Northeast, R3: Red River Delta, R4: North central, R5: South central, R6: Central highlands, R7: The south). Topography over the domain is obtained from the shuttle radar topography Mission (SRTM version 4.1, Jarvis *et al.*, 2008) [Colour figure can be viewed at wileyonlinelibrary.com]

24°N and longitudes of 102 and 110°E. Three-fourths of Vietnam's territory is covered by mountains and hills with several peaks higher than 3,000 m (Figure 1). The country can be divided into seven climatic sub-regions, namely Northwest (R1), Northeast (R2), Red River Delta (R3), North Central (R4), South Central (R5), Central Highlands (R6) and South (R7) (Nguyen and Nguyen, 2013; Phan *et al.*, 2009; Vu *et al.*, 2018; Raghavan *et al.*, 2017; Figure 1). Lying in an area of tropical monsoon, the whole country has a high temperature regime during boreal summer. In winter, the sub-regions R1–R4 experience a relatively cold period. The rainy season almost coincides with the summer monsoon season (May to October) in the northern sub-regions (R1–R3), Central Highlands (R6) and the South (R7), while it is shifted to transitional and early winter months in the North and South Central sub-regions (R4 and R5).

2.2 | Data

2.2.1 | Vietnam gridded precipitation data

The Vietnam gridded precipitation data (VnGP) data set (Nguyen-Xuan *et al.*, 2016) was constructed using daily data observed at 481 rain gauges in Vietnam. The VnGP

data set is available at daily timescale in two different spatial resolutions (0.25° and 0.1°) for the period 1980–2010. This data set has been referenced as the best source of gridded rainfall data currently available for Vietnam (Vu *et al.*, 2018). In this study, the daily data of VnGP at 0.25° spatial resolution was aggregated to monthly timescale and used as a reference data set to benchmark the model output for the baseline period 1986–2005.

2.2.2 | APHRODITE gridded temperature data

The Asian Precipitation Highly-Resolved Observational Data Integration Towards Evaluation of water resources (APHRODITE) data set is a product of the Research Institute for Humanity and Nature (RIHN), and the Meteorological Research Institute of Japan Meteorological Agency (MRI/JMA) (Yatagai *et al.*, 2012). Different versions of APHRODITE provide daily precipitation and temperature at 0.25° and 0.5° spatial resolutions for the Monsoon Asia. Temperature was released in the APHRODITE data version V1204R1 for the period 1951–2007 (Yasutomi *et al.*, 2011). Since a local gridded temperature data set for Vietnam is not yet available, the APHRODITE V1204R1 monthly data, which were aggregated from daily data, is used as a reference temperature data set for the baseline period 1986–2005 in the present study.

2.2.3 | Available water content

The soil parameter available water content (AWC) is popularly defined as the portion of water in soil that can be available for being absorbed by plants. The AWC can be calculated by subtracting the volumetric water content at field capacity with that one at wilting point (Mishra *et al.*, 2017). The AWC data used in this study are a global gridded data set at a resolution of 32×32 km. These data are a part of the Harmonized World Soil Database (Fischer *et al.*, 2008), which has been compiled from four sources: (a) the European Soil Database (ESDB); (b) the 1:1 million soil map of China; (c) various regional Soil Map of the World and the Soil and Terrain (SOTWIS Database); and (d) the Soil Map of the World (FAO, 2012). The AWC data are used in the calculation of the PDSI.

2.2.4 | RegCM4.3 RCM data

The downscaled outputs of six Coupled Model Intercomparison Project Phase 5 (CMIP5) GCMs by the

Regional Climate Model version 4.3 (RegCM4.3) are used in this study. The simulations were run in the framework of the CORDEX-SEA project, an intensive collaboration project that has been carried out by a community of scientists from within and outside of Southeast Asia (Tangang *et al.*, 2020). The list of GCMs and the names of the RCM experiments used in this study are provided in Table 1. The RegCM4.3 model was integrated continuously, covering the baseline period 1986–2005, and until the end of the 21st century for the RCP4.5 and RCP8.5 scenarios. The RegCM4.3 employed here is a hydrostatic, limited area model with a sigma (σ) vertical coordinate (Giorgi *et al.*, 2012). The physical parameterization schemes used in the RegCM4.3 downscaling experiments were selected based on the results of previous sensitivity studies (Juneng *et al.*, 2016; Cruz *et al.*, 2017; Ngo-Duc *et al.*, 2017), which included the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM3) radiative transfer scheme (Kiehl *et al.*, 1996), the sub-grid explicit moisture (SUBEX) large-scale precipitation scheme (Pal *et al.*, 2007), the modified Holtslag planetary boundary layer scheme (Holtslag *et al.*, 1990), the MIT-Emanuel convective scheme (Emanuel and Zivkovic-Rothman, 1999), and the BATS1e land surface scheme (Dickinson *et al.*, 1993). The model was configured with 18 vertical σ -levels and 25 km horizontal resolution for the CORDEX-SEA domain of 15°S to 27°N and 89°E to 146.5°E (Trinh-Tuan *et al.*, 2019; Tangang *et al.*, 2020). The RCP4.5 and RCP8.5 scenarios were selected as the middle and higher greenhouse gas concentration scenarios, respectively. The 6-hr outputs of 2 m-temperature and precipitation of six RCMs and their ensemble (ENS) were aggregated to monthly values for the baseline (BL, 1986–2005), mid-future (MF, 2046–2065) and far future (FF, 2080–2099) periods. The monthly precipitation and temperature data together with the AWC data set were used to compute the PDSI at each gridpoint. The drought characteristics were then calculated based on the obtained PDSI time series (Section 2.3).

2.3 | Palmer drought severity index and estimations of drought characteristics

The PDSI is used to examine changes in drought characteristics. This index was proposed by Palmer (1965) as a tool for evaluating the drought severity and its variations in time and space (Wells *et al.*, 2004). Although limitations still exist, the PDSI has become a popular measure for assessing and forecasting meteorological

TABLE 1 List of selected downscaled experiments with their respective driving CMIP5 GCMs used in this study

No.	Abbreviation of the RCM experiment	Driving GCM	Country and institution that developed the GCM	Horizontal resolution (degrees)
1	CNRM	CNRM-CM5	Centre national de Recherches Meteorologiques, France	1.41×1.41
2	HadG	HadGEM2	Hadley Centre, United Kingdom	1.25×1.875
3	MPI	MPI-ESM-MR	Max Planck Institute for Meteorology, Germany	1.875×1.875
4	ECEA	EC-earth	EC-Earth consortium, European Union	1.125×1.125
5	CSIR	CSIRO	Commonwealth Scientific and Industrial Research Organization, Australia	1.875×1.875
6	GFDL	GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory, United States	2.5×2.0
7	ENS	Ensemble mean of all six downscaled experiments		

drought (der Schrier *et al.*, 2011). The PDSI is calculated based on monthly precipitation, temperature, and AWC, from which the basic terms of the water balance equation, such as evapotranspiration, soil moisture loss, potential soil moisture recharge, and runoff are determined (Palmer, 1965; Alley, 1984; Yu *et al.*, 2019). Because the past moisture conditions are taken into account in the calculation process, the PDSI can be used to estimate the beginning and end of a drought spell and its duration. Since PDSI values are sensitive to AWC and evapotranspiration (der Schrier *et al.*, 2011; Alley, 1984), their spatial distribution might be affected by a lack of field survey data for determining AWC and by uncertainty in evaluating evapotranspiration. To date, there have been several modified versions of PDSI that were proposed to improve the PDSI's ability in capturing drought characteristics, such as the self-calibrating PDSI and a PDSI using different formulations of potential evapotranspiration (Dai, 2011a). Each version of PDSI has its own advantages and disadvantages. In this study the original PDSI, as in Le *et al.* (2019), is used.

The wet-dry state of weather conditions can be categorized by the values of PDSI, where drought levels are in the range of D1 to D4 (Svoboda *et al.*, 2002; Bonsal *et al.*, 2013): D1 corresponds to 'moderate drought', D2 to 'severe drought', D3 to 'extreme drought' and D4 to 'exceptional drought'. In this classification, the D1 to D4 levels are determined by the constant PDSI thresholds of -2 to -5 , respectively (Bonsal *et al.*, 2013).

In this study, drought levels were identified based on a percentile approach (Touma *et al.*, 2015). Although the drought characteristics were investigated for all drought levels, from moderate (D1) to

exceptional (D4) drought with percentiles in the range of 20 to 2%, we only focus on the extreme (D3) and exceptional (D4) drought events (i.e., the combination of D3 and D4; Le *et al.*, 2019). These combined events are defined using local percentile thresholds of 5% (LPT5) at each grid point. A drought condition was identified for a given grid point on a monthly basis when the PDSI is below LPT5. A drought spell is defined as a period of consecutive drought months. The drought characteristics examined in this study are: (a) Drought duration: the length (in months) of a drought spell; (b) Drought severity: the cumulative PDSI values of a drought spell; (c) Drought intensity: the ratio of severity and duration of a drought spell; (d) Inter-arrival time: the interval between the initial months of two consecutive drought spells; (e) Spatial (or geographic) extent: the percentage of the number of grid points at which a drought event occurs. For the first four characteristics, the mean (maximum) values are defined as average (longest or largest) values of all drought spells.

3 | RESULTS AND DISCUSSION

In this section, the performance of the RCM (i.e., RegCM4.3) in reproducing the spatial and temporal distributions of precipitation and temperature are first evaluated against the observational data for the historical (baseline) period 1986–2005. The projected changes in precipitation and temperature are then assessed by using the relative and absolute anomaly of the RCMs' outputs between the future and baseline periods, respectively. The two-tailed *t* test is applied to evaluate the statistical significance of the changes.

Lastly, the differences in drought characteristics between the MF and FF periods under the RCP4.5 and RCP8.5 scenarios in comparison to those in the baseline period are estimated and discussed.

3.1 | Performance of model in simulating temperature, precipitation, and drought characteristics over Vietnam

3.1.1 | Temperature and precipitation

Figure 2a,b shows the absolute (relative) differences in annual temperature (precipitation) between the RCM experiments and observations for the baseline period 1986–2005, while Figure 2c,d shows the differences in area-averaged temperature and precipitation over all grid points in each of seven sub-regions. It can be seen that most of the RCM simulations have a cold (i.e., negative) temperature bias of about 1–2°C over the whole country (Figure 2a). Particularly large biases can be observed in mountainous areas by the ECEA and GFDL experiments. In contrast, only the HadG experiment has an overall warm (i.e., positive) bias of about 1°C in the northern and central parts of Vietnam and weak cold biases in some parts of the south and Central Highlands. The ensemble mean shows cold biases of about 1.5–1.8°C in most of the sub-regions, and ~0.5°C in R3 (Figure 2c). For precipitation, the experiments show wet biases of ~10–100% over the whole country except for the CSIR and HadG experiments, which show dry biases of 5 to 20% over R1, R3, and R4 (Figure 2b). Overall, there is a large variation of precipitation biases among the experiments in the sub-regions, especially in R2, R6, and R7 (Figure 2d).

Figure 3 shows the differences between the monthly temperature and precipitation of the ENS of model simulations and observations for the baseline period. In general, the ENS exhibits a cold bias in temperature and wet bias in precipitation, which are consistent with those of the annual mean values (cp. Figures 2 and 3). However, the ENS shows a slight warm bias (less than 1°C) in the months from March to August and a large cold bias (3–4°C) from November to January over the northern sub-regions (R1–R4). The ENS can relatively well capture the monthly temperature from June to September in all sub-regions with biases ranging between $\pm 1^\circ\text{C}$ (Figure 3a,c).

For precipitation, the ENS reveals wet biases in most sub-regions throughout the year, except for R4 and R5 in October and November (Figure 3b). Precipitation is significantly overestimated in R6 and R7 during the dry season from November to April/May, and in R2 and R3 from November to January. The monthly variation of model biases for precipitation is quite large (Figure 3d), with the

largest biases in the winter months (100–350%) and the smallest ones in the summer months (below 100%).

3.1.2 | Drought characteristics

To evaluate the model performance in simulating drought characteristics, the relative differences (%) between the model simulations and observations were calculated for the baseline period (Figure 4). It can be seen that, the relative differences among the experiments are insignificant. In general, drought characteristics are underestimated over most parts of the country, with negative biases range from –20 to –10% for the mean drought duration and intensity, and from –40 to –20% for the mean severity. This underestimation in drought characteristics could be explained by the underestimated temperature (resulting in a decrease of the evapotranspiration) and overestimated precipitation (resulting in an increase of the soil moisture) of the model simulations, leading to overestimation of the PDSI. The model can well capture the drought inter-arrival time with negligible differences. However, it reveals an overestimation in simulating drought duration, severity and intensity in some parts of the sub-regions R1–R6.

3.2 | Projected changes in temperature and precipitation

3.2.1 | Changes on annual timescale

It is inferred from the above comparisons between the RCM simulations and observation that the model tends to underestimate temperature and overestimate precipitation. Most climate models have deficiencies and systematic biases that raise large uncertainties in their outputs (Wang *et al.*, 2014). Therefore, to cancel out the climate models' systematic biases for future climate, it is advisable to compute the changes in these climate variables between the future and baseline periods (Heinrich and Gobiet, 2012; Touma *et al.*, 2015).

Figure 5 shows the absolute and relative changes in temperature and precipitation, respectively, for the MF and FF periods under the RCP4.5 and RCP8.5 scenarios compared with the baseline period (hereafter denoted as MF45, MF85, FF45, and FF85, respectively). The changes are averaged over all grid points in each of seven sub-regions (R1–R7) and over the entire mainland of Vietnam (VN). It can be seen that the annual temperature in Vietnam is projected to increase by 1.0–1.5°C for MF45 and 1.5–2.0°C for MF85 compared with the baseline period (left panels of Figure 5). In FF85, the annual temperature

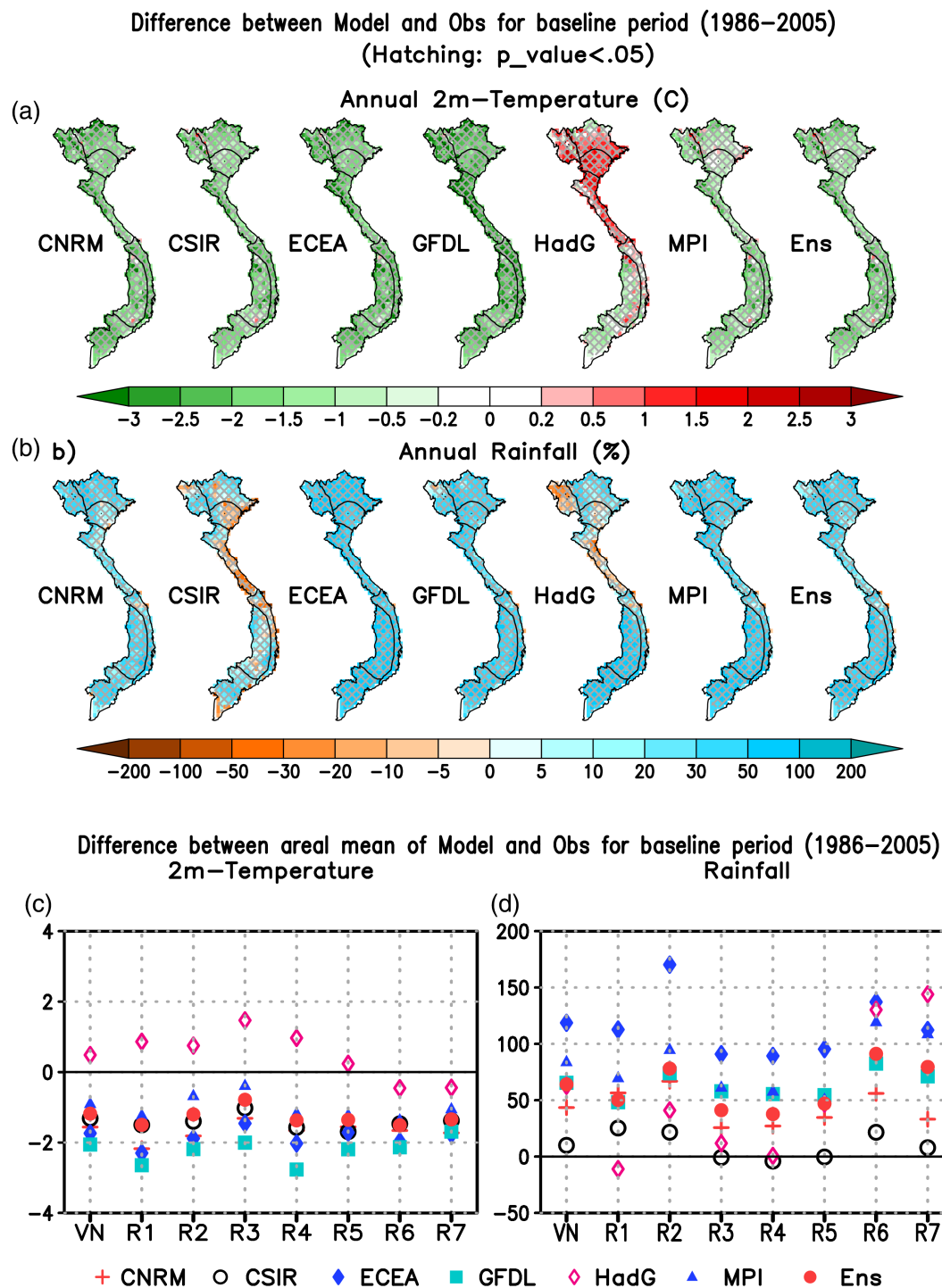


FIGURE 2 Differences of annual mean (a, c) temperature (°C) and (b, d) precipitation (%) between the RCM experiments and observations for the baseline period. Hatching in (a) and (b) indicates regions with p -values below .05. R1–R7 indicate seven climatic sub-regions (cf. Figure 1) [Colour figure can be viewed at wileyonlinelibrary.com]

is projected to increase by about 3.0–4.0°C, which is ~2°C higher than in FF45. The increase of temperature in R1–R4 is larger than in the other sub-regions. The lowest increase in temperature is projected for R7 (about 1.2°C for MF45 and still less than 3.0°C for FF8.5).

In contrast to the increase in temperature, the annual precipitation over Vietnam is projected to decrease (right

panels of Figure 5). The area-averaged precipitation over Vietnam slightly decreases by ~5% in MF45 and by ~10% in MF85, which is similar to the projected decrease in FF45. Precipitation is projected to decrease by ~20% in FF85 for the whole country. It is noteworthy that large differences in both projected temperature and precipitation exist among the experiments. The inter-simulation

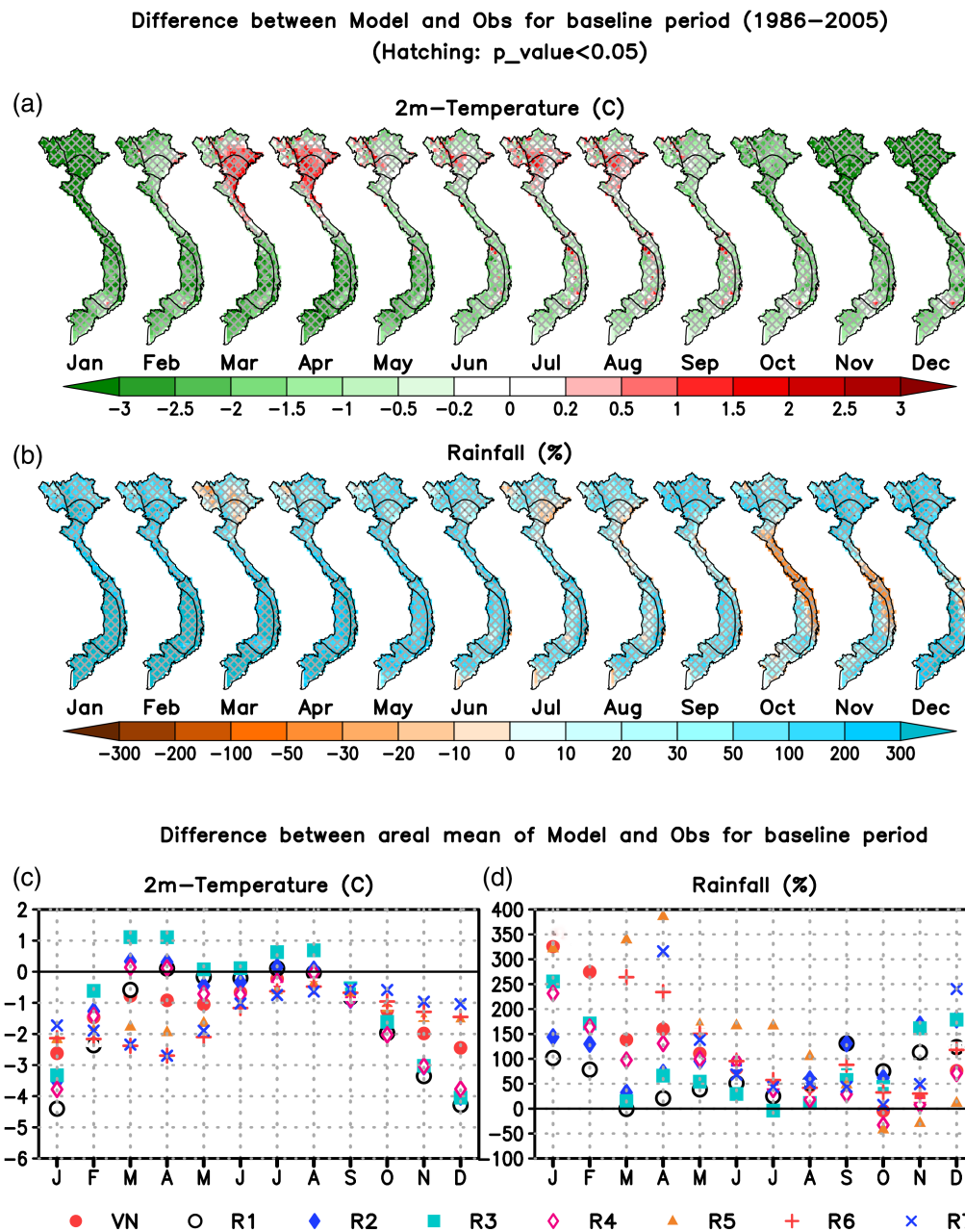


FIGURE 3 Same as Figure 2 but for monthly temperature and precipitation of the ENS [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/joc.7150)]

difference is largest in FF85 with a range of 2 to 5°C for temperature and of –50 to 20% for precipitation. On the other hand, the inter-simulation difference in projected precipitation for MF45 and MF85 is relatively small, which is about 10%.

3.2.2 | Changes on monthly timescale

The projected changes in monthly temperature are very similar to those for annual temperature (not shown). For monthly precipitation (Figure 6), the ENS product

is projected to decrease over the entire country during the summer monsoon season from April to October. From November to March, the ENS projects a decrease in precipitation over the southern sub-regions (R5–R7) and an increase over the northern parts of the country (R1–R3).

For the MF period, both scenarios show a decrease of 10–15% in precipitation in the wet season (May–October) in R2 but a slight increase of about 5% in some areas in both R2 (August) and R3 (October). Precipitation is projected to decrease in most months in the southern sub-regions with the largest changes occurring in the dry

Relative difference (%) of Drought Characteristics between model simulations and observations for the baseline period (1986–2005)

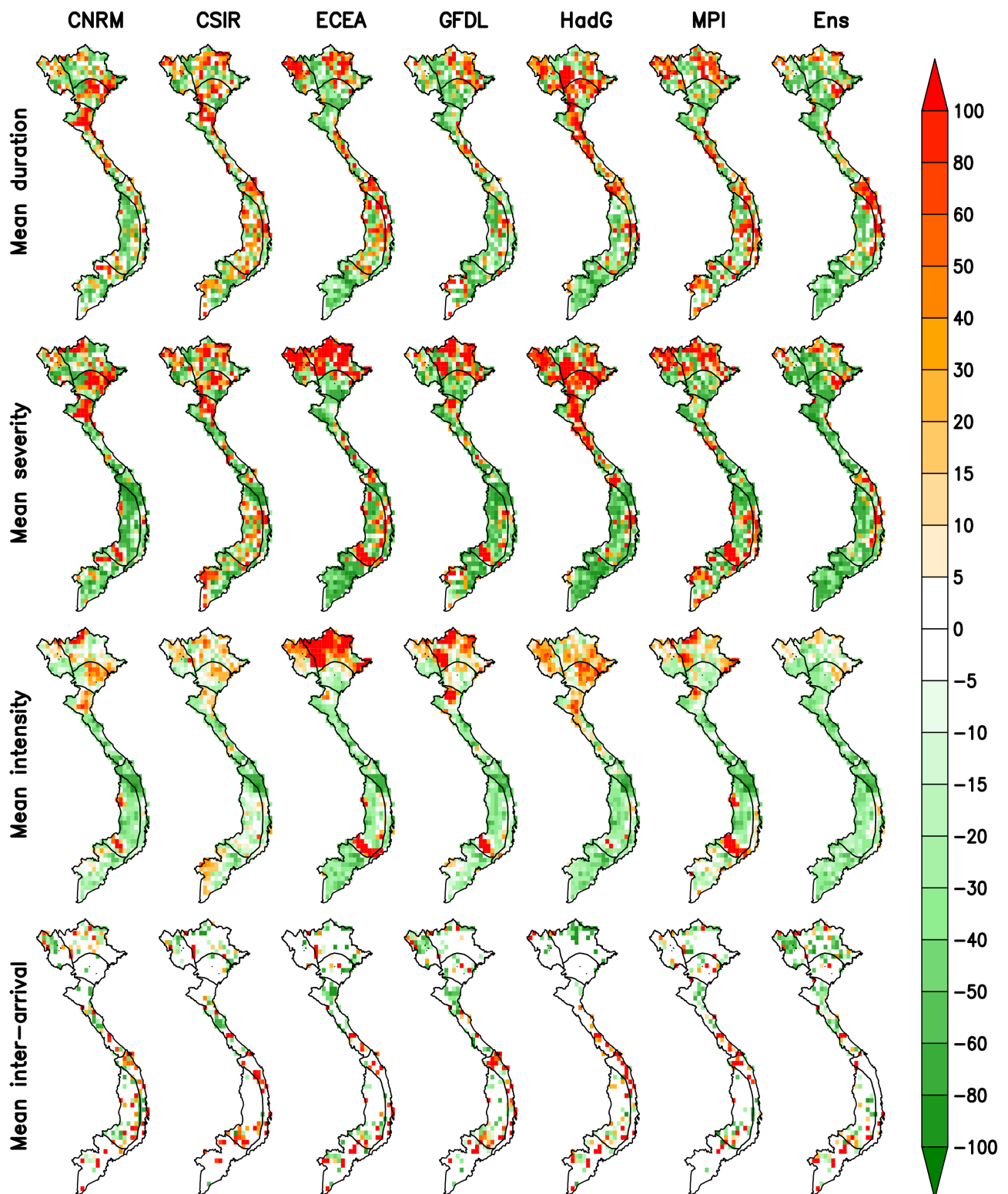


FIGURE 4 Relative differences (%) of drought characteristics between model simulations and observations in the baseline period (1986–2005) [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/joc.7150)]

season (November–April) and in months of the early wet season (May–July).

For the FF period, the spatial patterns of changes in precipitation are similar to those for the MF period. However, the magnitude of changes in the FF period is much larger. In the FF85 projections, precipitation in the southern sub-regions (R5–R7) is projected to decrease by about 30–40% in the dry season from November to April and in the early wet season (May–July). This implies that future drought could be more severe in these sub-regions due to the projected potential water deficit.

3.3 | Projected changes of drought characteristics

Figure 7 shows the projected changes in the model ensemble drought characteristics for the MF and FF periods under the RCP4.5 and RCP8.5 scenarios. The mean drought duration is projected to slightly increase over all sub-regions except for R5 (Figure 7a1). Significant increases are found in R3 and R4 in MF45, and in R7 and the southern parts of R4 in MF85. Although the projected changes in maximum drought duration have a similar spatial pattern to that of mean drought duration, the MF45 and FF45 show smaller increases than MF85 and FF85 (Figure 7a2). The largest increase in drought duration can be seen in R3 and R4 (~2–4 months, MF45) and in R7 (6–8 months, MF85). In general, drought duration is projected to increase in most sub-regions of Vietnam except for South Central (R5) and some parts of the Central Highlands (R6).

The projected changes in drought severity are generally consistent with those of drought duration (Figure 7b1,b2). Mean drought severity is projected to increase by 30 to 40% in R3, R4, and R7, and also in some parts of R6 (Figure 7b1). Mean drought severity is projected to decrease by ~20% in R5 and in some parts of R6 for MF45, MF85, and FF45. Maximum drought severity shows significant increases in R3, R4, and R7 of up to 60% (Figure 7b2). For both MF and FF periods, the RCP4.5 scenario shows a weaker increase in maximum drought severity than under the RCP8.5. A larger increased area of maximum drought severity is projected for the FF period than for the MF period.

Overall, the patterns of the projected changes in mean and maximum drought intensity are similar to those of drought severity, that is, areas with projected increases in drought intensity correspond to areas with projected increases in drought severity (Figure 7c1,c2). Specifically, under the RCP4.5 scenario, the mean drought intensity is projected to increase by 10–15% in R3, in the northern parts of R4, and in some parts of R6, and R7 for the MF

and FF periods (Figure 7c1). The RCP8.5 scenario projects stronger changes in drought intensity than the RCP4.5 scenario. The drought intensity slightly decreases by about 5% in some areas of R1, R2, R5, and R6. In comparison to the RCP4.5 scenario, the area with the projected increase in drought intensity under the RCP8.5 is larger, extending almost over the entire country. The spatial pattern of the future changes in maximum drought intensity is similar to that of mean drought intensity (Figure 7c2). In general, drought in R4, R6, and R7 is projected to be more intense under the RCP8.5 scenario for both MF and FF.

Figure 7d1,d2 shows the changes in mean and maximum drought inter-arrival time. The MF45 shows a decrease of between 3 and 5 months in R1, R4, some parts of R6, southern parts of R5, and R7, whereas MF85 shows an increase in most parts of the country except for R7. The patterns of the changes in mean inter-arrival time in FF45 and FF85 are more complex with a mixture of positive and negative changes over the country (Figure 7d1). However, MF45 clearly shows the projected decrease in drought inter-arrival time in R1–R3, some parts of R4, and R5–R7, implying that drought might occur more frequently in these areas in the future. The maximum inter-arrival time in Figure 7d2 indicates a more pronounced change when compared with the mean, implying that the interval between two drought events is shortened by up to 40% in certain areas.

3.4 | Annual cycle of the projected spatial extent of droughts

Figure 8 shows the mean annual cycle of future changes in the spatial extent of droughts. Overall, the changes in drought spatial extent, varying between –6 and 6%, reveal a pronounced seasonal variability. Relatively large variations are observed in R1, R2, R3, and R7. The spatial extent of drought is projected to increase not only in the dry season but also in the wet season. In particular, a stronger increase is found from February to April, that is, during the transition months between the dry and wet seasons, and from August to September. A slight decrease is projected for June and July in the summer monsoon season. It is noteworthy that the changes in the spatial extent of drought over the R4, R5, and R6 sub-regions are consistent among the RCM projections for both the MF and FF periods. Despite a large variation in the projected spatial extent of drought for R7 among the experiments, the drought area in this sub-region is projected to increase during the dry season and early months of the wet season. In general, the spatial extent of drought under RCP8.5 is projected to be larger than that under the RCP4.5 scenario in both the MF and FF periods.

Changes of Annual 2m-Temperature (C) and Rainfall (%) under scenarios of RCP4.5, RCP8.5 for periods 2046–2065 (MF) and 2080–2099 (FF) compared to 1986–2005 (BL)

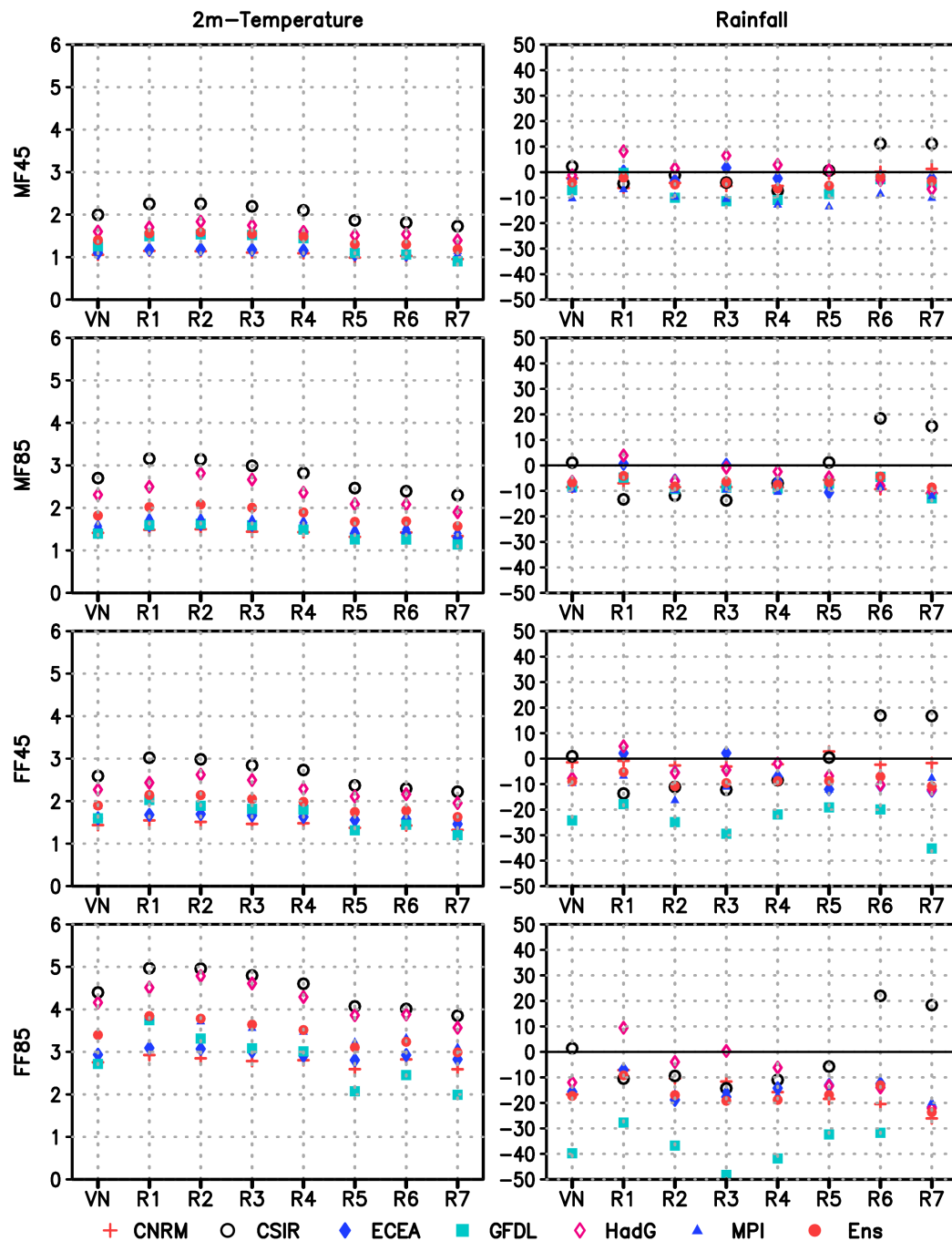


FIGURE 5 Absolute changes of area-averaged annual temperature (°C, left) and relative changes of area-averaged annual precipitation (% , right) in the MF and FF periods under the RCP4.5 and RCP8.5 scenarios projected by the different RCMs. R1-R7 indicate seven climatic sub-regions (cf. Figure 1), VN indicates the entire mainland of Vietnam [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/joc.7150)]

3.5 | Uncertainty in the projected change of drought characteristics

It needs to be noted that the changes in drought characteristics are determined based on the PDSI, which is basically dependent on projected temperature and

precipitation. In principle, an increase in temperature and a decrease in precipitation lead to an increase in drought. However, due to biases in the model simulations, most experiments underestimate temperature and overestimate precipitation, leading to possible inconsistencies between changes in drought characteristics and

Changes of Monthly Rainfall (%) under scenarios of RCP4.5, RCP8.5
for periods 2046–2065 (MF) and 2080–2099 (FF) compared to 1986–2005 (BL)

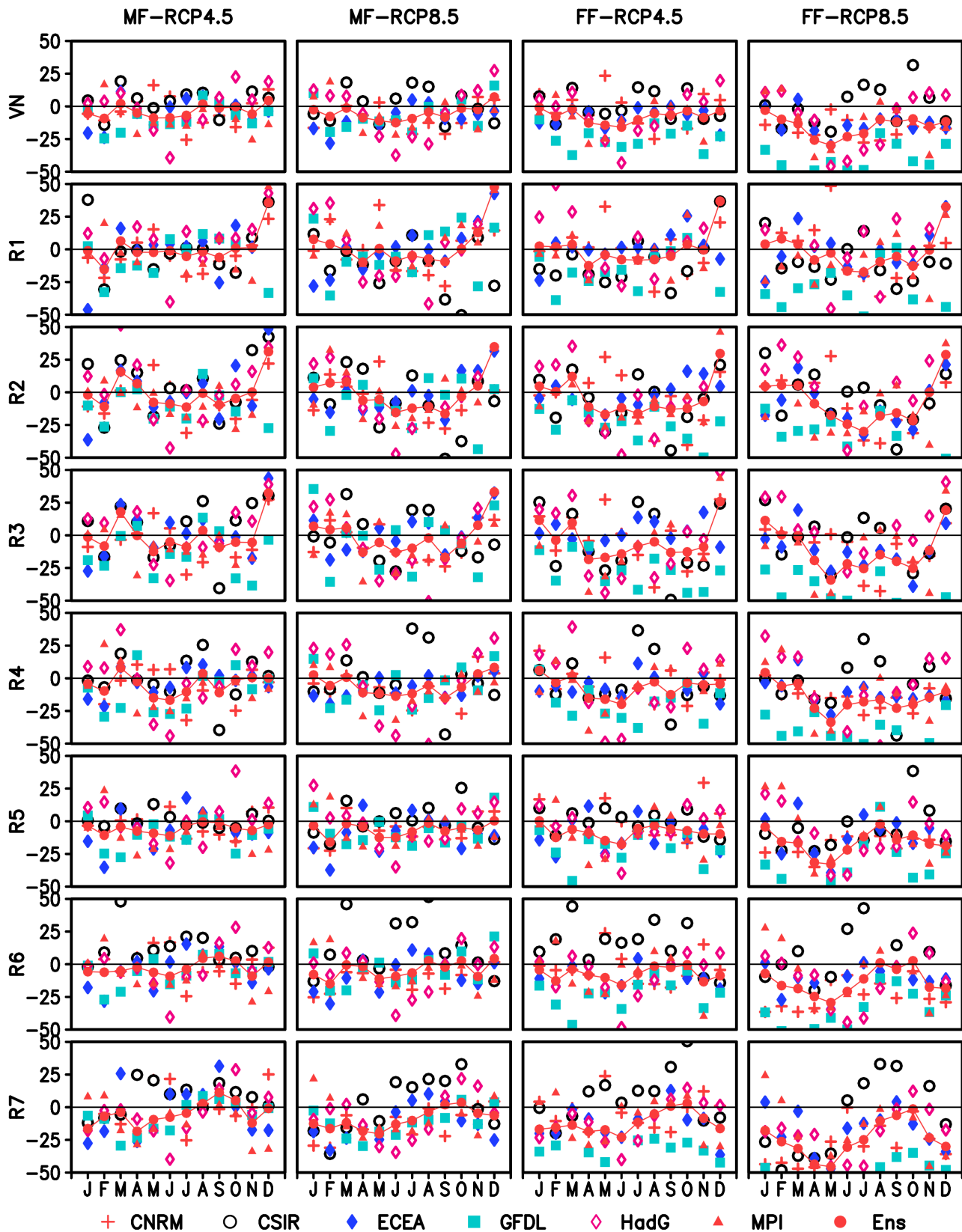


FIGURE 6 Relative changes of area-averaged monthly precipitation (%) in the MF and FF periods under the RCP4.5 and RCP8.5 scenarios projected by the different RCMs. R1–R7 indicate seven climatic sub-regions (cf. Figure 1), VN indicates the entire mainland of Vietnam [Colour figure can be viewed at wileyonlinelibrary.com]

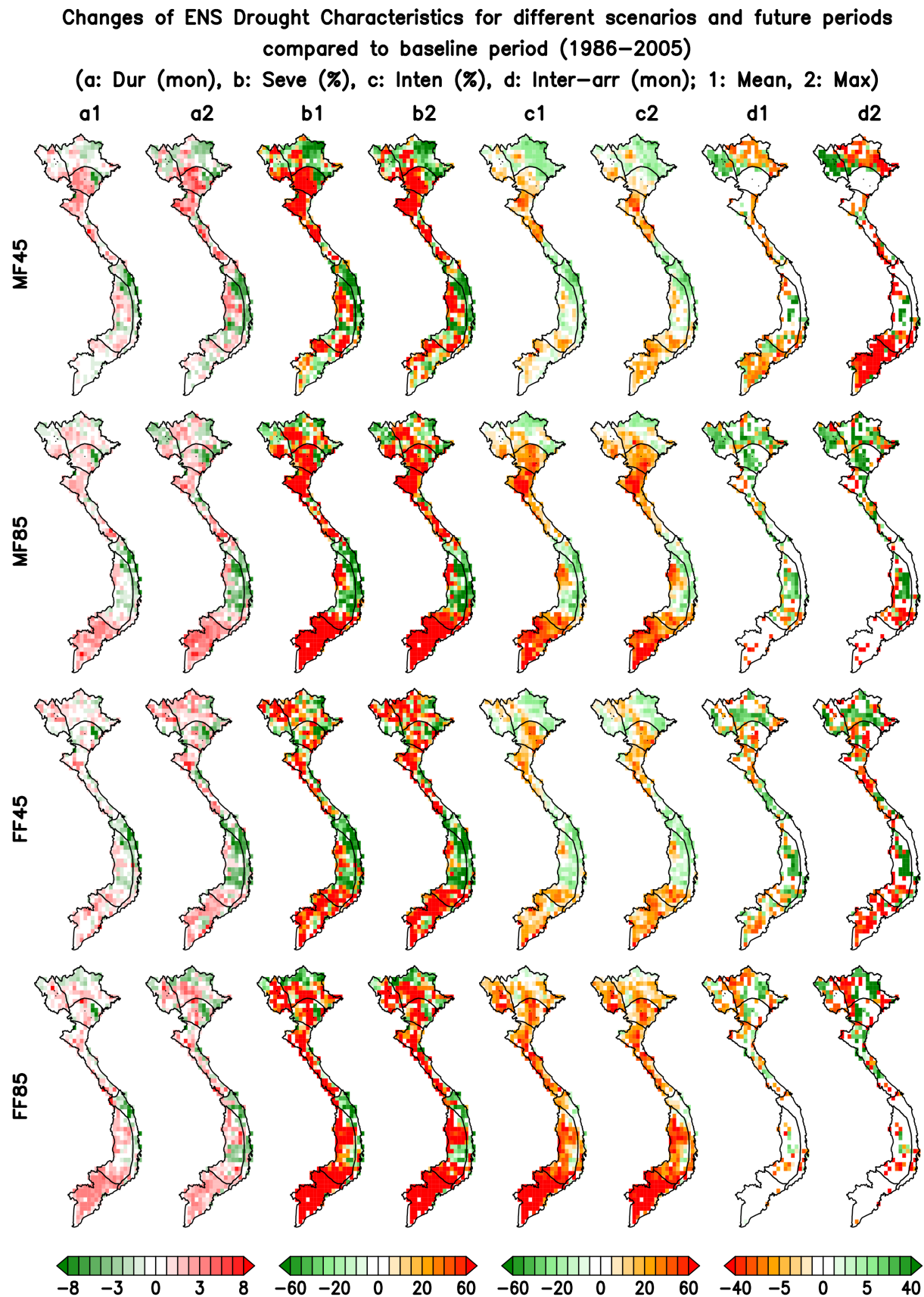


FIGURE 7 Changes of ENS drought characteristics in the MF and FF periods under the RCP4.5 and RCP8.5 scenarios. Left to right are the mean (1) and maximum (2) of drought duration (a, in month), drought severity (b, in %), drought intensity (c, in %), and drought inter-arrival time (d, in month) [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/joc.7150)]

Changes of Monthly Spatial Extent (%) under different scenarios and future periods (MF, FF) compared to baseline (BL) period

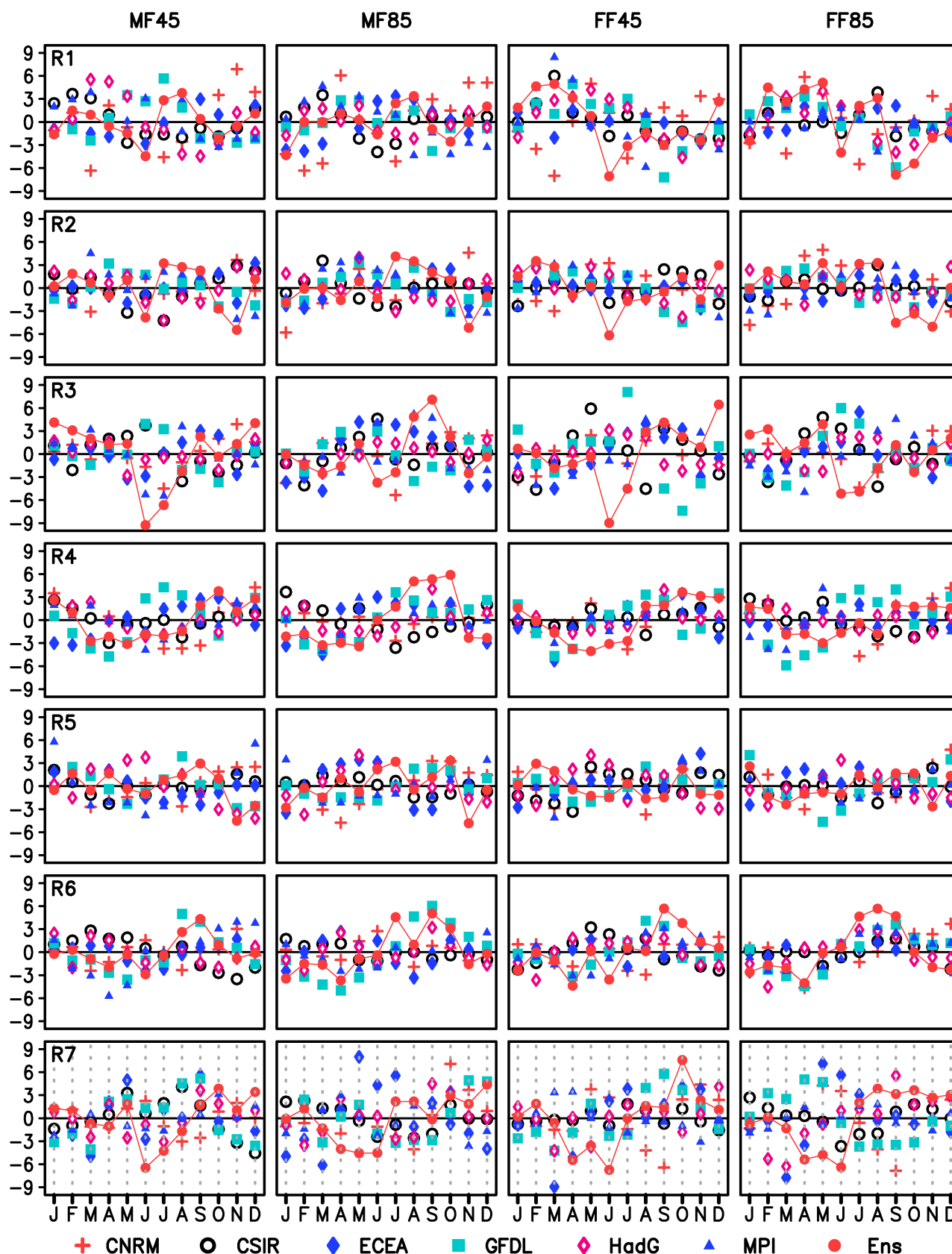


FIGURE 8 Changes in monthly geographic extent (%) in the MF and FF periods under the RCP4.5 and RCP8.5 scenarios over seven climatic sub-regions projected by the different RCMs. R1-R7 indicate seven climatic sub-regions (cf. Figure 1) [Colour figure can be viewed at wileyonlinelibrary.com]

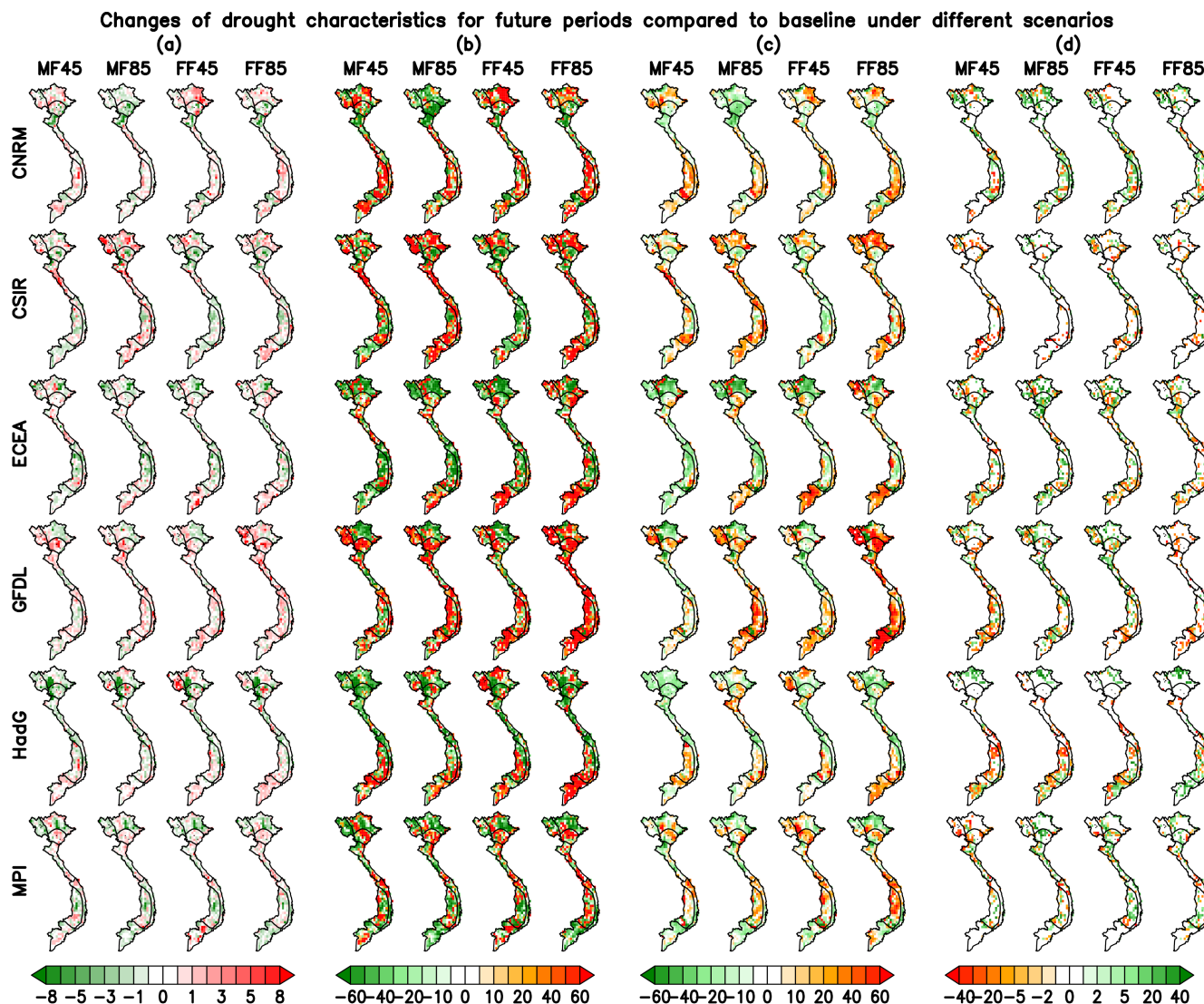


FIGURE 9 Changes in mean drought characteristics in the MF and FF periods under RCP4.5 and RCP8.5 scenarios projected by different RCMs: Duration (a, in month), severity (b, in %), intensity (c, in %), and inter-arrival time (d, in month) [Colour figure can be viewed at wileyonlinelibrary.com]

changes in temperature and precipitation. Despite the pronounced increases in drought duration, severity, intensity and spatial extent, and decreases in the inter-arrival time of drought over the sub-regions R1–R4, and R6–R7, these changes do not correspond to the projected changes in temperature and precipitation in terms of magnitude and spatial pattern. The overestimation of future precipitation might be the main reason for this inconsistency, although cold biases in projected temperature might also be another cause (Bonsal *et al.*, 2013).

Figure 9 compares the changes in mean drought characteristics projected by each of the RCM experiments. The GFDL projections show positive changes in drought duration and severity over the entire country, while the ECEA projections show a decrease in most areas (Figure 9a,b). For drought intensity, the ECEA

projections show a decrease, while most of the other experiments indicate an increase (Figure 9c). The largest uncertainty occurs in the projected changes of drought inter-arrival time (Figure 9d), which shows a mixture of increasing and decreasing changes among the RCM experiments.

Even though the GFDL projections show a pronounced increase in drought, this experiment reveals the highest biases in simulated temperature and precipitation. Therefore, the drought characteristics in the GFDL projections may contain a large uncertainty, especially in the FF period. The CSIR projections reveal an increase in drought duration, severity, intensity, and a decrease in inter-arrival time over the entire country in MF85. Although the ECEA projections show a considerable increase in drought over a large part of R2 and some

areas of R7, there is a decrease in drought duration, severity, and intensity over other areas. The other projections, namely CNRM, HadG, and MPI, show a mixture of positive and negative changes in drought characteristics over the country.

In summary, due to the variety of biases in the projections of temperature and precipitation among the RCM experiments, there may exist a large uncertainty in the projected changes in drought characteristics. For example, the opposite signs between temperature and precipitation biases could result in a reduction of the magnitude of projected change in drought characteristics under the different scenarios. Although the systematic biases in simulating temperature and precipitation could be cancelled out by calculating the changes between the future and present climate (Section 3.2.1), such biases might not be completely eliminated in the changes of drought characteristics.

4 | CONCLUSIONS

The projected changes in drought characteristics over Vietnam were evaluated using six RCM experiments from the CORDEX-SEA project. The different drought characteristics were calculated using the PDSI, which was based on precipitation and temperature from the RCM outputs. Our results showed that the drought duration, severity, and intensity are projected to increase in most climatic sub-regions of Vietnam. In particular, drought is projected to be more severe in the Red River Delta (R3), the North Central region (R4), and the South (R7). Drought spatial extent is projected to increase in the dry season and the transition months between the dry and wet seasons. The mean inter-arrival time of droughts is found to be shortened in many areas, implying a tendency towards a reduced return period of droughts in the future. Several main findings can be summarized as follows:

- When compared with observations, biases in both temperature and precipitation are found in the baseline simulations. Overall, the RCM experiments exhibit an overestimation of precipitation and an underestimation of temperature.
- The temperature over Vietnam is projected to increase by about 1.5–2.0°C for MF45, MF85, and FF45, and by 3.0–4.0°C for FF85. Precipitation is projected to decrease by about 10–20% for MF45, MF85, FF45, and by up to 30% for FF85. Increasing temperature combined with decreasing precipitation could lead to water deficits in the top soil layers, resulting in increased drought severity and intensity, especially in the late months of the dry season and in the early months of the wet season.

- Projected changes in drought characteristics indicate a more pronounced increase in drought duration, severity, and intensity over the Red River Delta (R3), the North Central region (R4) and in the South (R7) of Vietnam when compared with the other sub-regions. This suggests that drought risks could increase in these sub-regions, especially in R3 and R7, which are the main areas of rice production in Vietnam.
- Due to uncertainties in model simulations leading to the cold bias in temperature and the wet bias in precipitation, the projected changes in drought characteristics might not fully correspond with the increase in temperature and decrease in precipitation in terms of magnitude and spatial patterns.

To date, a number of different drought indices, other than the PDSI, have been proposed, depending on the perception about drought as well as the application purposes (Zargar *et al.*, 2011). Each index has its own advantages and disadvantages. Drought characteristics are determined from the selected drought index and from the way of how they are defined (i.e., how thresholds are established). In this study, the local percentile threshold of 5% (LPT5) was applied to the PDSI at each gridpoint. Thus, the obtained results might not be fully representative for all research contexts.

Due to their coarse spatial resolution, GCMs may not provide detailed enough information for drought management at the local scale. Therefore, the use of RCMs is credible, since RCMs could resolve sub-grid scale processes and are consequently more appropriate for detailed impact studies and for adaptation to climate change. The results of this study are thus essential and play a vital role in providing information that can be used for drought risk management and decision-making for the agricultural sector and water resource management in Vietnam.

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