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A high-resolution climate experiment over part of Vietnam and the Lower Mekong Basin: performance evaluation and projection for rainfall

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ABSTRACT

This study first evaluates the performance of three model experiments in representing rainfall over part of Vietnam and the Lower Mekong Basin for the historical period 1986-2005. The three experiments include the Coupled Model Intercomparison Project Phase 5 (CMIP5) EC-EARTH Global Climate Model (GCM) and two downscaling runs based on a regional climate model at 25km resolution with the GCM forcing (RCM-25km) and at 5km resolution with the RCM-25km forcing (RCM-5km). Verifications against observations show that the experiments generally capture the spatial distribution of climatological rainfall. While the GCM well represents the observed average rainfall cycles, its coarse resolution limits its capability in reproducing extreme rainfall values. The downscaling experiments do not clearly show their advantage in simulating average rainfall but exhibit significant added values when representing extreme rainfall in the study region. The RCM-5km does not outperform its driving 25km experiment in representing the mean and extreme rainfall values, suggesting that having a better resolution may not compensate for having a good model configuration with appropriate physical schemes. Analysis of climate projection for the far future period 2080-2099 under two representative concentration pathways (RCP) scenarios, RCP4.5 and RCP8.5, reveals that the downscaling experiments can modify the change direction of future rainfall obtained with the GCM. While the EC-EARTH GCM generally projects wetter tendencies of up to 50%, the downscaling experiments project a general decrease of down to -50% under both scenarios over the study domain. Regarding extreme rainfall, the annual maximum 1-day rainfall amount (RX1day) is projected to increase for the three experiments. The simple daily intensity index (SDII) future changes follow those of the annual rainfall values.

Keywords: Dynamical downscaling, regional climate model, rainfall, climate change, Vietnam, Lower Mekong Basin.

1. Introduction

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicated that recent changes in the climate are widespread, rapid, and intensifying in almost every region on Earth

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(Arias et al., 2021). Climate change has caused severe impacts in many places in the world and many aspects of life.

In Southeast Asia (SEA), the observed temperature has increased in the past decades (Gutiérrez et al., 2021). However, the tendencies of observed rainfall are not spatially unified among different sources of data and seasons (Gutiérrez et al., 2021). Regional climate models (RCMs) also give very different rainfall simulation results in SEA. For example, Aldrian et al. (2004) simulated rainfall in Indonesia using the Max Planck Institute REMO RCM and showed that REMO generally reproduced the spatial pattern of monthly and seasonal rainfall over land but overestimated rainfall over the ocean. They also demonstrated that the quality of driving data could significantly affect the performance of the REMO experiments. Phan et al. (2009) used the Regional Climate Model version 3.0 (RegCM3) forced by the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 reanalysis for the period 1991-2000 and found that the simulated rainfall of wet and dry seasons was respectively underestimated and overestimated in Vietnam. Francisco et al. (2006) showed that RCM rainfall in the Philippines is sensitive to lateral boundary conditions. Nguyen-Thi et al. (2019) showed wet biases over Southeast Asia by the RegCM4.3 simulations forced with six different driving Global Climate Models (GCMs). The choice of cumulus and air-sea flux parameterizations in the RCM experiments highly affected simulated rainfall results in SEA, particularly over the Maritime Continent (Juneng et al., 2016; Ngo-Duc et al., 2017).

Future changes of projected rainfall in SEA are also highly dependent on sub-regions, seasons, and the numerical experiments used (e.g., Chotamonsak et al., 2011; Kieu-Thi et al., 2016, Manomaiphiboon et al., 2013; Ngo-Duc et al., 2014; Tangang et al., 2019; Tangang et al., 2020). Over Thailand, Manomaiphiboon et al. (2013) conducted fine-resolution (20km) RegCM3 experiments driven by outputs of the ECHAM5/MPI-OM GCM under three emission scenarios of IPCC (SRES) (Nakicenovic et al., 2000). They found a shift to drier conditions over the Central-East and South sub-regions, while no substantial changes in average precipitation are seen in the upper sub-regions of Thailand. Meanwhile, under the representative concentration pathways (RCP) scenarios RCP4.5 and RCP8.5 (van Vuuren et al. 2011), rainfall was projected to be generally wetter and drier in the northern-central-eastern parts and the southern parts of Thailand, respectively (Tangang et al., 2019). Over Vietnam, Ngo-Duc et al. (2014) used three RCMs to project future changes under the SRES A1B scenario and showed that the most significant changes existed over the coastal plain of Central Vietnam, particularly in the winter monsoon season. Rainfall was projected to decrease during June-July-August (JJA) and increase during September-October-November (SON) in Central Vietnam for both SRES and RCP scenarios (Kieu-Thi et al., 2016; Trinh-Tuan et al., 2019). Over the entire SEA, it is necessary to highlight the recent effort of the Southeast Asia Regional Climate Downscaling (SEACLID) community in conducting high-resolution (25km) multi-model regional climate simulations under the framework of the Coordinated Regional Climate Downscaling Experiment-Southeast Asia (hereafter referred to as CORDEX-SEA) (Tangang et al., 2020). Based on these simulations, several analyses have been carried out. Tangang et al. (2020) showed that mean rainfall was projected to increase by 10-20% throughout the 21st century over Indochina during December to February (DJF), while a drying tendency was projected over the Maritime Continent. The annual maximum 1-day precipitation amount (Rx1day) was projected to increase over SEA (Supari et al., 2020) and experience significant and robust changes in intensity in Indochina (Tangang et al., 2018).

Located in the mainland of SEA, Thailand and Vietnam rank 9th and 13th respectively among the most affected countries by impacts of weather and climate-related extreme events (e.g., tropical cyclones, floods, heat waves) according to the Climate Risk Index for 2000-2019 (Germanwatch, 2021). Note that Southern Vietnam and Northeast Thailand belong to the Lower Mekong Basin, one of the most important food baskets of the world with a large area of most fertile soil. However, this region is vulnerable to extreme climate events such as floods and drought, affecting food production and daily human life (MRC 2009; World Bank 2012; Kundzewicz et al., 2013; Hijioka et al., 2014). In the Lower Mekong Basin, flood and drought events have intensified in the past 30 to 50 years (Hijioka et al., 2014). Despite the high exposure and vulnerability of the region to climate extremes, available literature indicates the existence of large knowledge gaps in understanding how future climate change and climate extremes would affect the different sectors of the society (Hijioka et al., 2014). Note that the recent RCM results for the region, such as those of the existing CORDEX-SEA experiments, usually have a typical resolution of around 25km. This resolution is still too coarse to accurately represent the complex terrain and topographical features of the region (e.g., Nguyen Dinh and Lai Vinh 2021; Loi et al., 2021). In some other areas, efforts have been made to perform very high-resolution simulations (~3km or less) which can explicitly resolve convection processes (e.g., Hentgen et al., 2019; Kendon et al., 2021). With our existing computing resources, it is still a major challenge to conduct similar cloud-resolving simulations. Nevertheless, high-resolution data (finer than 25km) are required for detailed analysis of future climate and extremes relevant to some impact assessment applications or appropriate adaptation measures. In response to these requests, in this study, we conduct a high (5km) resolution RCM experiment and examine the role of model resolution in rainfall simulation and future projection over part of Vietnam and the Lower Mekong Basin.

2. Study domain, numerical experiments, and observed data

2.1. Study domain

The study domain is located in the southeastern edge of the Indochina peninsula, from 100°E-110°E, 9°N-18.5°N (Figure 1b). The domain, covering Central Vietnam, Central Highlands, Southern Vietnam, Southern Laos, Cambodia, and Northeast Thailand, is a combination of coastal areas, plains, mountains, highlands, and especially the Lower Mekong Basin. The study domain is one of five climate change key vulnerable domains selected for research in the second phase of the CORDEX-SEA project (Tangang et al., 2020). This project aims to provide high-resolution climate information (5km) to facilitate the assessments of climate change impact in these areas. As we could collect station data in Vietnam's sub-regions (R2-R4) and Northeast Thailand (R1), the analysis in this study will focus more on these sub-regions.

2.2. Numerical experiments

In this study, numerically simulated climate data from three different sources are used. The first source of climate data used is that of the European Community Earth-System Model (EC-EARTH, denoted as GCM in the figures of this study) (Hazeleger et al. 2010) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) collected from the Earth System Grid Federation (ESGF) system. The second source of climate data used is the hydrostatic 25km RegCM4.7 (Giorgi et al., 2012) dynamically downscaled EC-EARTH (hereafter called RCM-25km) over the CORDEX-SEA domain (Figure 1a; Tangang et al., 2020). The parameterization schemes employed in the RCM-25km experiment, including the Massachusetts Institute of Technology (MIT)-Emanuel convective scheme (Emanuel and Zivkovic- Rothman 1999) and the Biosphere-Atmosphere Transfer (BATS13) land surface scheme (Dickinson et al., 1993), were as described by Juneng et al. (2016), Cruz et al. (2017), and Ngo-Duc et al. (2017). Lastly, the RCM-25km is further downscaled to the 5km resolution for the study area (Figure 1b) using the same RegCM4.7. The 5km experiment (RCM-5km), conducted under the non-hydrostatic mode, uses the MIT-Emanuel convective scheme over land, the Kain-Fritsch (KF) scheme (Kain and Fritsch, 1993) over ocean, and the updated land surface scheme (Community Land Model; CLM45) (Oleson et al., 2013). All the climate data used covers the historical period of 1986-2005 and the future period of 2006-2099 under two future climate change scenarios, i.e., RCP4.5 and RCP8.5.

2.3. Observed data

The Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset (Funk et al., 2015) is used to evaluate the spatial distribution of model data. CHIPRS has a high spatial resolution of 0.05º (~5km) at monthly, pentad and daily time steps for the period from 1981 to the near present. It was constructed based on rain gauge and satellite observations. Besides, we also use rainfall data measured at 27 *in situ* stations in the study area (Table 1, Figure 1b), which are obtained from the Hydro-Meteorological Services of Thailand and Vietnam, and from the National Centers for Environmental Information (NCDC), NOAA (ftp://ftp.ncdc.noaa.gov/pub/data). The temporal resolution and period selected for comparison and data collection are monthly and 1986-2005, respectively.

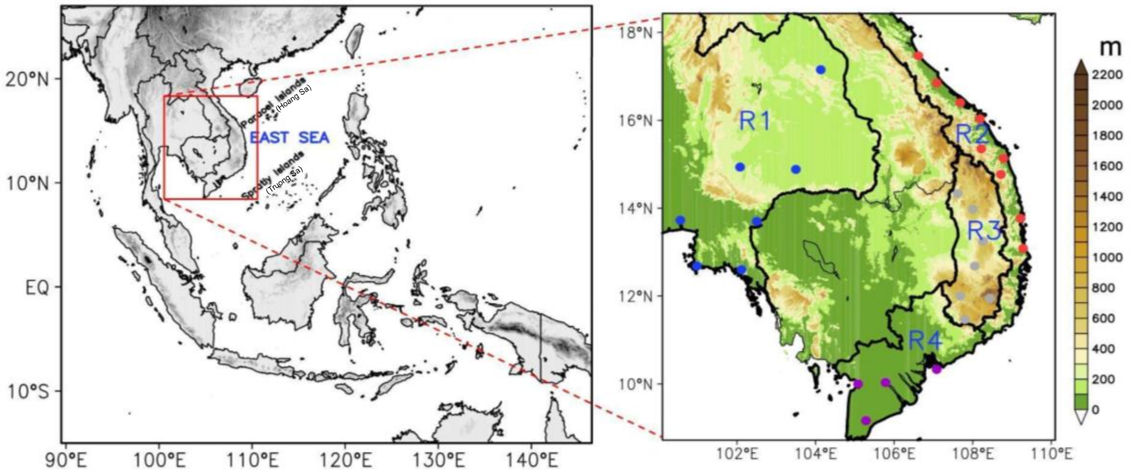

Figure 1. (a) The CORDEX-SEA domain and (b) the study domain including Northeast Thailand (R1), the Central Coast region (R2), Central Highlands (R3), and Southern part of Vietnam (R4). Locations of 27 rainfall stations used in the analysis are also displayed in color dots

Table 1. List of 27 rainfall stations used in the study

No.	Station Name	Longitude (°E)	Latitude (°N)	Sub-region
1	BANGKOK	100.56	13.73	Northeast Thailand (R1)
2	SAKON-NAKHON	104.133	17.15	
3	KHORAT	102.079	14.94	
4	SURIN	103.5	14.88	
5	ARANYAPRATHET	102.504	13.7	
6	SATTAHIP	100.983	12.68	
7	CHANTHABURI	102.117	12.6	
8	BATO	108.717	14.767	Central Vietnam (R2)
9	DANANG	108.183	16.033	
10	DONGHA	107.083	16.85	
11	DONGHOI	106.617	17.467	
12	HUE	107.683	16.4	
13	QUANGNGAI	108.783	15.133	
14	QUYNHON	109.217	13.767	
15	TRAMY	108.217	15.35	
16	TUYHOA	109.283	13.083	
17	AYUNPA	108.26	13.25	Central Highlands (R3)
18	BAOLOC	107.8	11.467	
19	BMTHUOT	108.05	12.683	
20	DAKNONG	107.683	12	
21	DALAT	108.433	11.95	
22	KONTUM	107.617	14.333	
23	PLEIKU	108	13.983	
24	CAMAU	105.283	9.167	Southern Vietnam (R4)
25	CANTHO	105.783	10.033	
26	RACHGIA	105.083	10	
27	VUNGTAU	107.083	10.33	

3. Results and Discussion

3.1. Model performance during the historical period 1986-2005

The ability to simulate rainfall by the GCM, RCM-25km, and RCM-5km is first evaluated through comparison with the CHIRPS dataset via the annual and seasonal mean values calculated for the historical period 1986-2005 (Fig. 2). For the annual mean (ANN), the observational-based CHIRPS spatial pattern shows that high rainfall is more concentrated in the east of the study domain and forms a narrow band in the southwest, with a common value at more than 6mm/day. Northeast Thailand and parts of the Lower Mekong, including Cambodia's Tonle Sap region, have relatively less rainfall, generally less than 4 mm/day. The GCM and RCM-5km represent the observed ANN spatial pattern quite well, while the RCM-25km exhibits much larger rainfall amounts than observed, with average ANN values possibly up to more than 20 mm/day in various areas. This high amount of rainfall simulated by RCM-25km is largely due to the cumulus parameterization and, to some extent, the land surface scheme used (Juneng et al., 2016; Chung et al., 2018). Although the RCM-5km represents the difference in rainfall between the east and west of the domain well, the rainfall area of the RCM-5km is narrower with much higher values in some places, especially in the east, while some other areas are drier than observed. This deficiency is possibly due to the high resolution of the RCM-5km, which favors local convective activities and the interactions between atmospheric motions (e.g., southwest monsoon) and local topography, resulting in significant changes to the fine-scale rainfall pattern (Navale and Singh 2020).

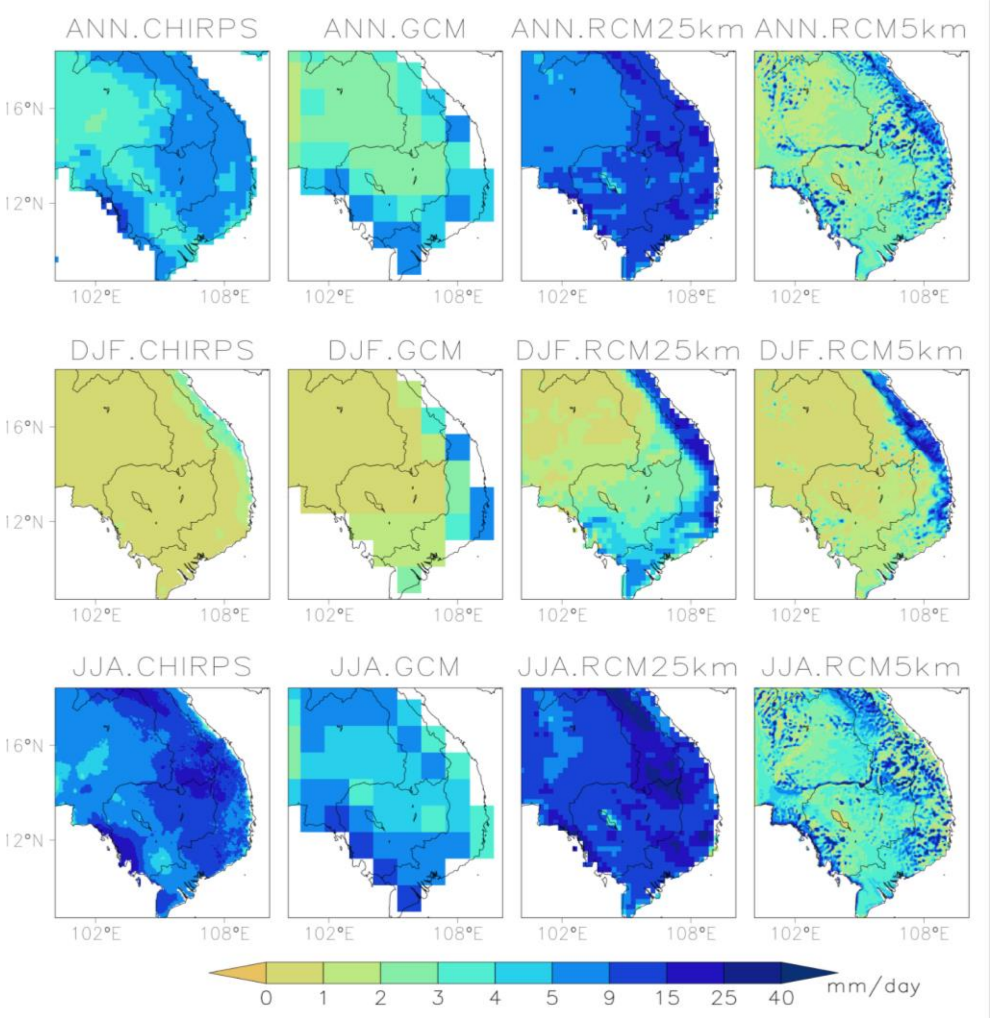

Figure 2. Spatial distribution of rainfall averaged for the period 1986-2005 given by CHIRPS and simulated by the global EC-EARTH model (GCM), RCM-25km and RCM-5km. Top, middle and bottom panel shows the annual, DJF and JJA average, respectively

In the dry months of DJF, the difference in rainfall between the R2 sub-region (Central Vietnam) and the rest is obvious. Rainfall in R2 is greater due to the interaction between the northeast monsoon and the local topography (Nguyen-Le et al., 2015). The experiments capture well the spatial distribution of DJF rainfall. However, all three experiments exhibit an overestimation of the rainfall in R2, especially the RCM-25km and RCM-5km. The RCM-25km also overestimates rainfall in other areas, including Central Highlands (R3), Southern Vietnam (R4), and parts of Laos and Cambodia. In the summer months (JJA), the RCM-25km represents the observed spatial pattern quite well, although its rainfall values are still overestimated. When compared to CHIRPS, the EC-EARTH GCM seemingly underestimates rainfall in JJA. Meanwhile, the RCM-5km produces even lower rainfall than the GCM over the study domain in general.

However, particularly high rainfall values, as a direct result of the local topography's effect, are simulated for some areas. Since the prevailing wind direction during JJA is the southwest, CHIRPS and the numerical products show relatively higher rainfall on the windward sides of mountainous areas, especially the western part of the Truong Son Mountain range.

It is also to be noted here that obtaining accurate rainfall values by combining satellite and station data sources is still a challenge. The number of in situ stations used to build the CHIRPS dataset is relatively low within the study area (Funk et al., 2015). Moreover, satellite-derived products still have difficulty estimating orographic rainfall and rainfall in coastal areas (Ngo-Duc et al., 2013; Trinh-Tuan et al., 2019). Therefore, to strengthen the evaluation results, we analyze the models' performance using the 27 in situ stations listed in Table 1.

Figure 3 shows the climatological monthly rainfall for the period 1986-2005. It can be seen that CHIRPS can capture the seasonal rainfall cycles at the stations in all four sub-regions. Meanwhile, rainfall cycles simulated by the three experiments are quite different from the station observed data. In the whole region, the simulation results of the RCM-25km are higher than those observed, especially in the dry season and early summer months. The RCM-25km can closely reproduce observations in some rainy months, e.g., in July-September over Southern Vietnam. In the dry season and early summer months, the RCM-5km better exhibits averaged rainfall than the RCM-25km. However, the RCM-5km results have much larger variability between stations compared to that of CHIRPS, especially in the rainy season in Southern Vietnam and Northeast Thailand. In Central Highlands, the RCM-25km overestimates rainfall throughout the year, while the RCM-5km and GCM underestimate rainfall. Despite having the coarsest resolution, the GCM produces relatively the best results on the climatological seasonal cycle of simulated rainfall in Southern Vietnam and Northeast Thailand. This indicates that the GCM can simulate rainfall well in areas where the topography is not too complex. The overestimate of rainfall simulated by the RCM-25km over the study area was previously mentioned by Juneng et al. (2016) and Ngo-Duc et al. (2017). They found that the MIT-Emmanuel convective scheme (Emanuel and Zivkovic-Rothman, 1999) used in the experiment, although giving relatively good results over Southeast Asia, overestimates rainfall in the Indochina peninsula. Therefore, it is necessary to reexamine the choice of physical schemes in a next RCM downscaling experiment over the study region. It is worth mentioning that the RCM-5km experiment applied the mixed convective scheme (MIT-Emanuel over land and KF over ocean) and the CLM4.5 land surface scheme, which are different from those used in the RCM-25km. Thus, investigating the sensitivity of high-resolution RCM experiments with the physical parameterization schemes over the study domain will be an exciting research direction to be implemented in the future.

For further comparison of the performance of the different experiments, Taylor diagrams (Taylor, 2001) for the climatological monthly time series of rainfall at the 27 stations of the four sub-regions are constructed (Fig. 4). In the diagram, each symbol corresponds to the statistical performance of an experiment at one station. The standard deviation ratio (NSTD) of model data to that of the observation is represented by radial distance, and the correlation (CORR) is represented by polar angle. Thus, the “reference” point on the horizontal axis (i.e., unit correlation) at the unit distance from the origin represents the station-observed data. Taylor (2001) showed that the linear distance between each symbol and the reference point is proportional to the centered root mean square difference (RMSD) between the model and the observations.

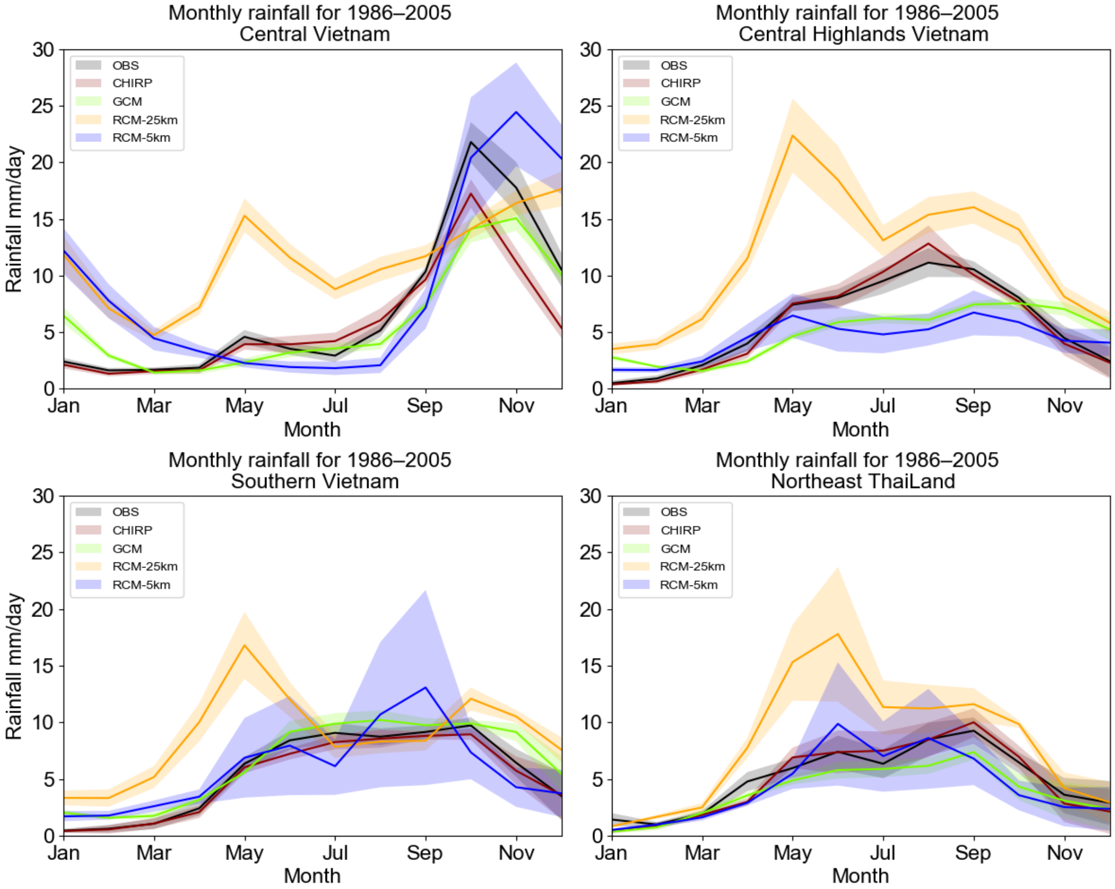

Figure 3. Seasonal cycles of rainfall averaged for the period 1986-2005 over the 4 study sub-regions. Colored lines show the average value, and colored shaded areas present the range of values at stations in the 4 study sub-regions

Figure 4 also shows that CHIRPS represents the observed values at the stations well, especially in Southern Vietnam. The correlation between CHIRPS and station data is generally above 0.9. The rainfall variability of CHIRPS is underestimated in Central Vietnam and overestimated in the Central Highlands of Vietnam and Northeast Thailand. The EC-EARTH model exhibits a relatively small RMSD (RMSD ~ 0.5) and a relatively high correlation value (CC ~ 0.9), although the variability of the data series is lower than that observed at most stations. The RCM-25km and RCM-5km experiments give results quite far from the observations, especially for rainfall variability. The RCM-25km exhibits higher rainfall variability across most of the sub-regions, except for Central Vietnam. Possibly, 25km is still too coarse to capture the observed rainfall variability in a narrow and complex terrain such as Central Vietnam, leading to underestimating rainfall there. In contrast, the RCM-5km underestimates rainfall variability in all regions except Central Vietnam. Thus, changing the model resolution and possibly the physical schemes will significantly affect the simulated rainfall values. Not every experiment with a higher resolution will better simulate climatological monthly rainfall values. In the following, we will examine whether the change in resolution will help improve simulated extreme rainfall values.

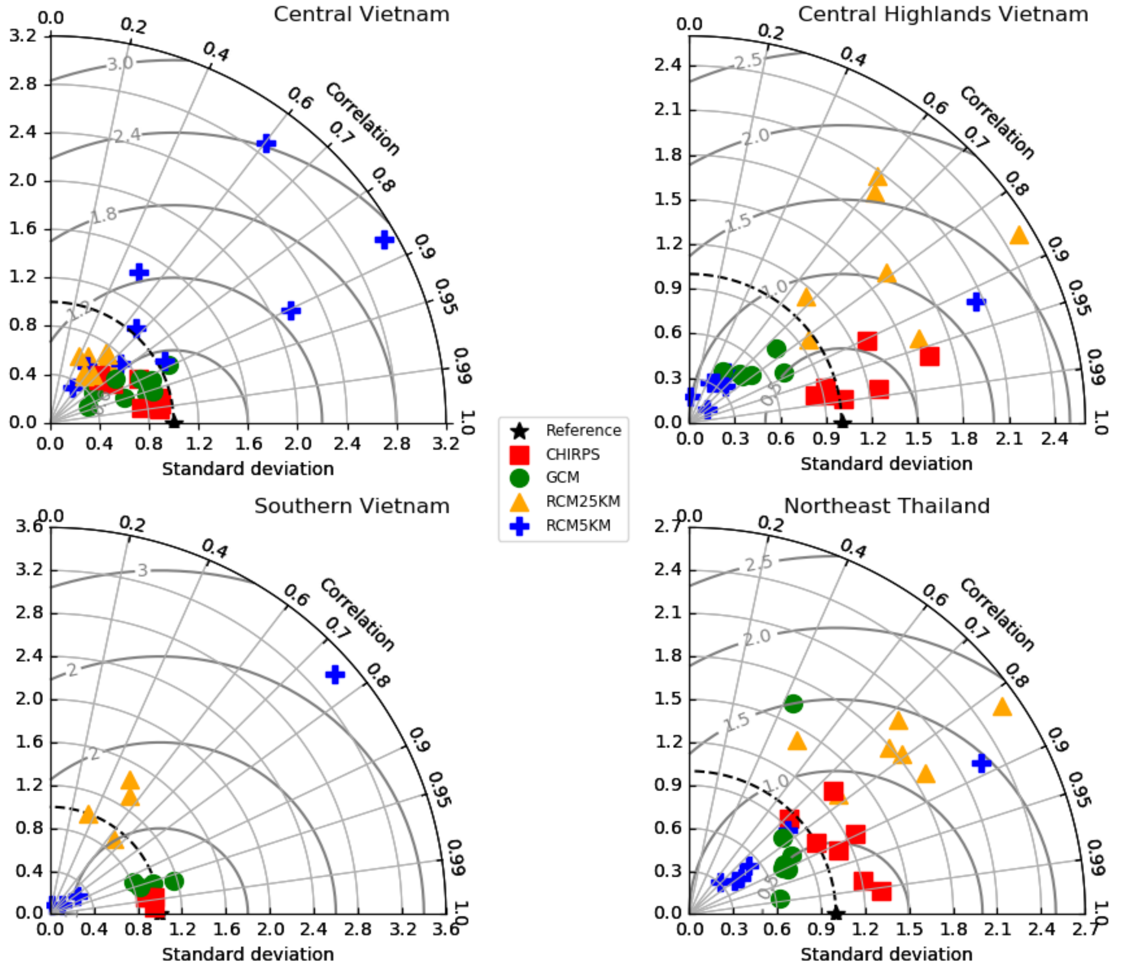

Figure 4. Taylor diagram for the climatological monthly time series of rainfall over the 27 stations in the four sub-regions

Figure 5 displays the distribution of rainfall density for the 20-year data series (1986-2005). The observational-based CHIRPS dataset well performs the observed distribution in the Central Highlands and Central Vietnam but underestimates extreme values in Southern Vietnam and Northeast Thailand. Although the average rainfall values of the GCM are close to the station observations (Figs. 3, 4), its extreme rainfall values are significantly underestimated in all four sub-regions, specifically for days with rainfall greater than 100 mm. Meanwhile, the RCM-25km better represents extreme rainfall compared to its driving GCM in all sub-regions. Note that the RCM-25km is also better than CHIRPS in Southern Vietnam and Northeast Thailand. The better performance of the RCM-25km compared to that of the GCM is consistent with the findings of Ngo-Duc et al. (2017), that downscaling experiments exhibit added values over Southeast Asia when representing extreme rainfall. However, as the resolution increases, the RCM-5km tends to overestimate extreme values in three out of four sub-regions. Therefore, this study's 5km experiment does not outperform its driving 25km experiment in representing both the mean and extreme rainfall values. As discussed above, it is likely that the choice of physical schemes was not really optimal for the 5-km run. Thus, in this case, having a better resolution does not compensate for having a good model configuration with appropriate physical schemes.

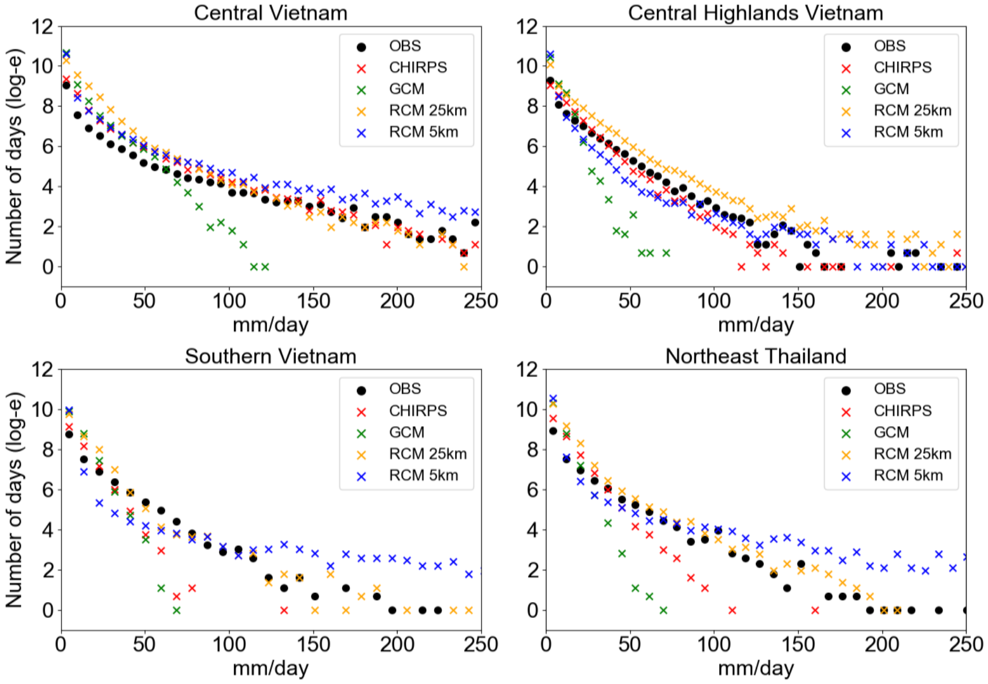

Figure 5. The number of days (in $\log_e$ scale) corresponding to each 5mm-bin rainfall intensity for the 20-year daily data series (1986-2005) at the 27 stations. Values for each 5mm-bin are computed for the stations (OBS, black), CHIRPS (red), GCM (green), RCM-25km (orange), and RCM-5km (blue)

3.2. Rainfall projection

Figure 6 shows mean rainfall in the historical (1986-2005) and future (2080-2099) periods under the RCP4.5 and RCP8.5 scenarios, simulated and projected by the GCM, RCM-25km, and RCM-5km. According to the GCM projections, Northeast Thailand tends to be wetter with about 1 mm/day rainfall increase in some parts under RCP4.5 and RCP8.5 compared to the baseline, while no significant changes are found there by the RCM-25km. The RCM-5km results point out about 1 mm/day drier status in several eastern areas of Northeast Thailand. For the RCM-25km, only the southernmost point of Vietnam is a bit drier under RCP8.5 compared to RCP4.5 and the baseline, which is contradictory to the GCM - a little wetter there. In general, the RCM-25km does not represent any pronounced changes in Southern Vietnam among the baseline and two RCPs. The RCM-25km exhibits a much wetter condition than the GCM and RCM-5km. More greatly detailed results are displayed by the RCM-5km than the GCM and RCM-25km.

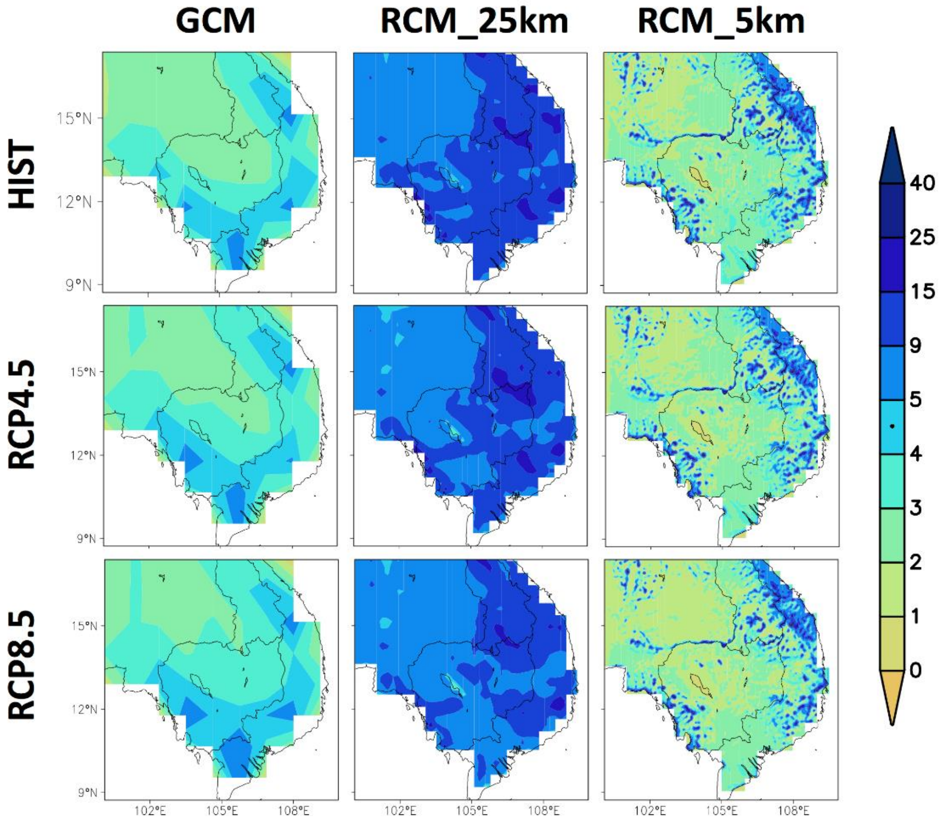

Figure 6. Mean rainfall (mm/day) for the historical period (1986-2005) (1st row), at the end of the 21st century (2080-2099) under the RCP4.5 (2nd row) and RCP8.5 (3rd row) scenarios by the GCM (1st column), RCM-25km (2nd column) and RCM-5km (3rd column)

Relative rainfall changes projected by the GCM, RCM-25km, and RCM-5km at the end of the century (2080-2099) compared to the baseline 1986-2005 under two RCPs are displayed in Fig. 7. The GCM generally projects wetter tendencies over most of the study area except for some parts in the Central Highlands and Central Vietnam with 5%-10% dryness under RCP4.5 and some tiny areas (only two grid cells) in Central Vietnam and Southern Laos (5% dryness) under RCP8.5. In general, the RCM-25km and RCM-5km produce similar change patterns under each RCP with more detailed information for the RCM-5km. For the RCM-25km, almost the whole Vietnam region and Cambodia are drier under RCP8.5, and only some small parts of Central Highlands and Cambodia are a bit wetter under RCP4.5. Most of Southern Laos are wetter under RCP4.5, and these wetter areas are reduced significantly under RCP8.5 by the RCM-25km and RCM-5km. The drier tendency (5%-30%) is very prominent in most Northeast Thailand, Southern Laos, Cambodia, Central Highlands, and Southern Vietnam under RCP8.5 by the RCM-5km. The statistical significance of future rainfall changes is defined via the t-test (Daniel, 2006). The differences (at the 5% significance level) with baseline rainfall are much larger for RCP8.5 than RCP4.5. The ratios are 71%, 47%, and 46% under RCP8.5 (46%, 25%, and 16% under RCP4.5) by the GCM, RCM-25km and RCM-5km, respectively (Fig. 7).

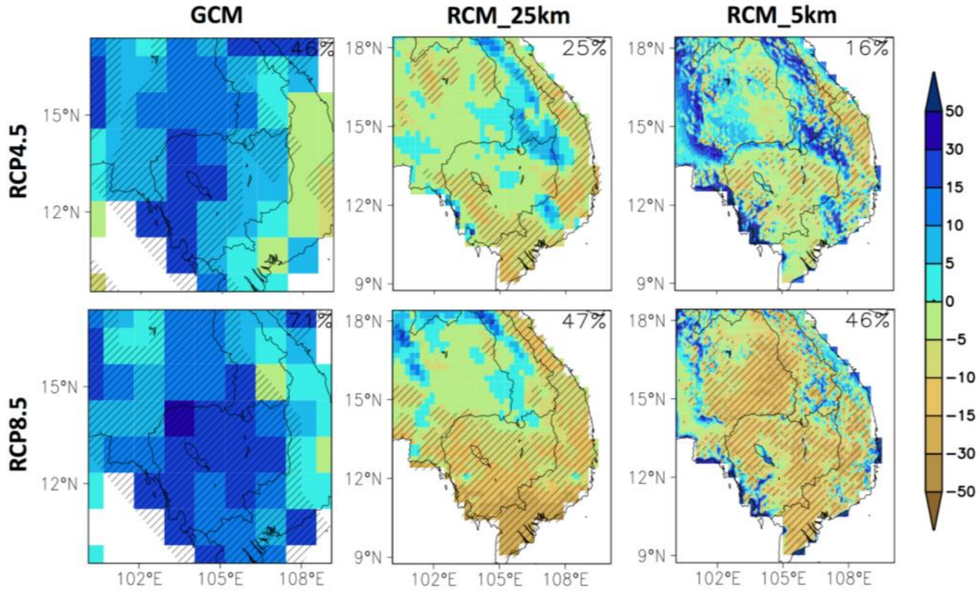

Figure 7. Relative rainfall changes (%) projected by the GCM (1st column), RCM-25km (2nd column), RCM-5km (3rd column) under the RCP4.5 (1st row), and RCP8.5 (2nd row) scenarios for the period 2080-2099 compared to the baseline 1986-2005. Hatch pattern indicates the difference at the 5% significance level under the t-test. The number in each panel's upper-right corner shows the percentage of grid points with significant differences

Figure 8 and Fig. 9 display the projected changes of two extreme indices, which are the annual maximum 1-day rainfall amount (hereafter called Rx1day) and the simple daily intensity index (hereafter called SDII), i.e., the ratio of annual total rainfall to the number of wet days (days with rainfall amount ≥ 1mm).

In general, the three experiments project Rx1day increase across most of the study domain, except for some scattered areas where the RCM-25km and RCM-5km project about 5-30% decrease. Projected increases under both RCP4.5 and RCP8.5 are prominent (by 100% or even more) in many locations in the study area, especially by the RCM-5km. Previously, Manomaiphiboon et al. (2013) projected heavy rainfall increases in intensity and frequency in Northeast Thailand under 3 SRES scenarios. Rx1day was also projected to increase over SEA (Supari et al., 2020) and Indochina (Tangang et al., 2018) under RCP4.5 and RCP8.5. For our present study, it is worth mentioning that the Rx1day changes by the RCM-25km and RCM-5km are not always in high agreement. The ratios of grid points with significant changes under the t-test are relatively high for the GCM (42% and 64% under RCP4.5 and RCP8.5, respectively) and relatively small for the RCM-25km (4.2%) and RCM-5km (less than 3.2%) under both RCPs (Fig. 8).

The trend in projected increases in extreme rainfall intensity could be attributed to both atmospheric thermodynamic and dynamic changes in warmer future climates (Emori and Brown, 2005). Increased availability of atmospheric water content as mean temperature increases possibly contributes to extreme rainfall increase under global warming (Raymond 2000; Bretherton et al., 2004; Muller et al., 2009). Moreover, increasing sea surface temperature in the context of future climate change may also increase extreme rainfall (Muller et al., 2011; Cubasch et al., 2013).

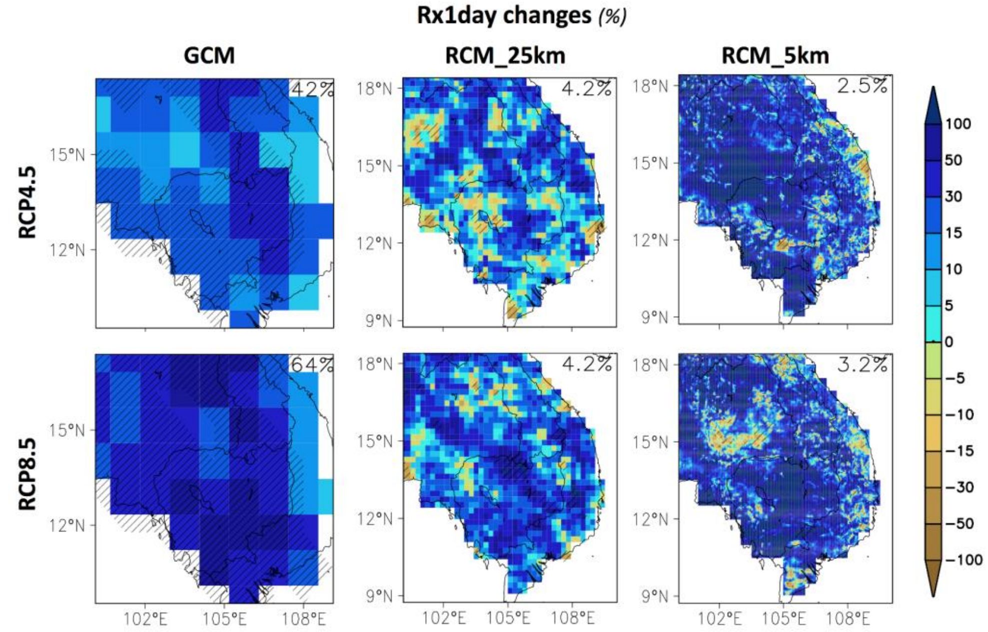

Figure 8. As in Figure 7 but for Rx1day changes (%)

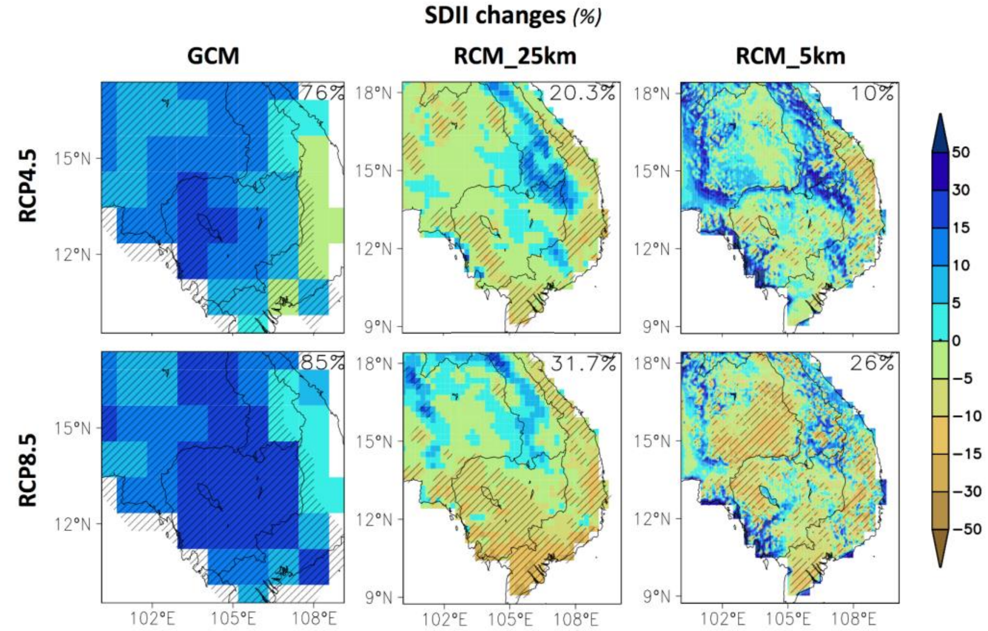

Figure 9. As in Fig. 7 but for SDII changes (%)

Performances of the RCM-25km and RCM-5km are relatively consistent in projecting the SDII changes under both RCPs, except for some parts in Central Vietnam. The RCM-5km provides more detailed patterns than the RCM-25km. While the GCM shows a significant general increase in projected SDII over the study area, the RCM experiments display an SDII decrease under both scenarios. The higher the model resolution is, the smaller percentages of grid points with significant changes under the t-test are, and these percentages under RCP8.5 are more extensive than those under RCP4.5 (Fig. 9). The changes of SDII are consistent with relative rainfall changes displayed in Fig. 7. The reason is that the RCM experiments overestimate the number of wet days (not shown), and the percentage changes in the number of wet days are much more minor than the percentage changes in annual rainfall amount (not shown), leading to the dominant role of the rainfall changes (Fig. 7) in those of SDII (Fig. 9).

5. Conclusions

This paper examines the performance of three model experiments, including the EC-EARTH GCM, and the downscaling RCM-25km and RCM-5km, in the historical period (1986-2005) and assesses future climate projection of the 21st century over part of Vietnam and the Lower Mekong Basin under both RCP4.5 and RCP8.5 scenarios. The following are key findings of the analysis:

(i) The experiments generally capture the spatial distribution of climatological rainfall for the period 1986-2005, especially the distinct difference during DJF between the east and west of the study domain.

(ii) The satellite and station-based CHIRPS dataset performs well at the 27 stations used in this study in terms of climatological seasonal cycles. However, CHIRPS underestimates extreme values in Southern Vietnam and Northeast Thailand. Thus, it is recommended to be careful when using satellite-derived products in studying extreme rainfall events.

(iii) The EC-EARTH GCM well represents the observed rainfall cycles in the four sub-regions of this study. However, its coarse resolution limits its capability in well reproducing extreme rainfall values.

(iv) Although the downscaling experiments do not clearly show their advantage in simulating average rainfall, they exhibit significant added values when representing extreme rainfall in the four sub-regions. However, the high 5km resolution experiment does not outperform its driving 25km experiment in representing both the mean and the extreme rainfall values. Thus, it can be concluded that having a better resolution may not compensate for having a good model configuration with appropriate physical schemes.

(v) The downscaling experiments can modify the change direction of future rainfall. While the EC-EARTH GCM generally projects wetter tendencies over most of the study domain, the downscaling RCMs project a general decrease under both scenarios. Regarding extreme rainfall, RX1day is projected to increase for the three experiments while the SDII changes follow the annual rainfall values.

This study suggests that future efforts should focus on reexamining the choice of physical schemes used in the next RCM downscaling experiment. The pre-defined schemes used in this study might not suit the region and the high 5km run. It is also of interest to perform a downscaling experiment at a convection-permitting resolution (~3km or finer) in the future, which allows to represent small-scale processes better and avoid possible significant biases induced by the convective scheme (Kendon et al., 2021). Finally, the results of this study are based on the experiments realized with only one given GCM. Further analysis of an ensemble of simulations with different driving GCMs would be instrumental in assessing the uncertainty of future rainfall projections over the study region.

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