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Future changes in precipitation extremes over Southeast Asia: insights from CMIP6 multi-model ensemble

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Abstract

Past assessments of coupled climate models have indicated that precipitation extremes are expected to intensify over Southeast Asia (SEA) under the global warming. Here, we use outputs from 15 climate models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) to evaluate projected changes in precipitation extremes for SEA at the end of the 21st century.
The results suggest that CMIP6 multi-model ensemble medians show better performances in characterizing precipitation extremes than individual models. Projected changes in precipitation extremes linked to rising greenhouse gas (GHG) emissions (represented by the latest proposed Shared Socioeconomic Pathways) increase significantly over the Indochina Peninsula and the Maritime Continent. Substantial changes in the number of very heavy precipitation days (R20mm) and the intensity of daily precipitation (SDII) indicate that such locally heavy rainfall is likely to occur over a short time and that more precipitation extremes over SEA are probable in a warmer future. This is consistent with projections from the Coordinated Regional Downscaling Experiment and CMIP5 models. The present study reveals the high sensitivity of the precipitation extremes over SEA, and highlights the importance of constrained anthropogenic GHG emissions in an ambitious mitigation scenario.

1. Introduction

How fast is too fast? The global mean temperature in 2019 was around 1.1 ± 0.1 °C above pre-industrial levels, which may have been the second warmest year on record (WMO 2019). Latest reports confirm that the global mean temperature is warming at a rate of 0.1 °C–0.3 °C per decade. Restricting global warming to below 2 °C (or the preferred lower limit of 1.5 °C) is the committed target of the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement (UNFCCC 2015). To achieve this ambitious target under current anthropogenic greenhouse gas (GHG) emissions seems like a race against time. However, while the present fossil fuel investments and mitigation strategies do not support the strategy to keep global warming below 1.5 °C, the coronavirus disease 2019 (COVID-19) pandemic has dramatically led to a temporary reduction of both GHG emissions and air pollutants around the world since February 2020 (Smith *et al* 2019, Forster *et al* 2020, Le Quéré *et al* 2020). Despite this, looking ahead, the global cooling response to the pandemic is likely to be sudden and small, and would not drastically alter future increases in climate extremes.

It has been well demonstrated that the current rapid global warming has tended to intensify precipitation extremes in tropical regions through changes in atmospheric water vapor content, circulation patterns, and moisture supply, which in turn significantly influence natural ecosystems, water management, and agriculture in less-developed countries (Allen and Ingram 2002, Zhai *et al* 2005, Held and Soden 2006, Vecchi *et al* 2006, Hulme 2016, Marotzke *et al* 2017, Sillmann *et al* 2017, Chen and Sun 2018, Nikulin *et al* 2018). Southeast Asia (SEA), an area characterized by a large coastal population in complex terrains, is generally considered to be one of the

Table 1. Summary of the 15 CMIP6 models used in this study.

No.	Model	Institution/Country	No. of atmospheric grid points (lon. × lat.)
1	BCC-CSM2-MR	BCC-CMA/China	320 × 160
2	CanESM5	CCCMA/Canada	128 × 64
3	CESM2-WACCM	NCAR/USA	288 × 192
4	CNRM-CM6-1	CNRM-CERFACS/France	256 × 128
5	CNRM-ESM2-1	CNRM-CERFACS/France	256 × 128
6	FGOALS-g3	LASG-IAP/China	180 × 90
7	GFDL-ESM4	GFDL-NOAA/USA	360 × 180
8	INM-CM4-8	INM/Russia	180 × 120
9	INM-CM5-0	INM/Russia	180 × 120
10	IPSL-CM6A-LR	IPSL/France	144 × 143
11	MIROC6	MIROC/Japan	256 × 128
12	MPI-ESM1-2-HR	MPI/Germany	192 × 96
13	MPI-ESM1-2-LR	MPI/Germany	192 × 96
14	MRI-ESM2-0	MRI/Japan	192 × 96
15	UKESM1-0-LL	MOHC/UK	192 × 144

hot spots of global warming (IPCC 2013). SEA has already suffered from intensified climate extremes with increased occurrences of widespread flooding and drought during the past decades, events that are likely to continue in the future (IPCC 2014, Villafuerte and Matsumoto 2015, Tangang *et al* 2019, 2020, Supari *et al* 2020, Zhu *et al* 2020b). Interannual and interdecadal variations of climate in SEA have a significant relationship with the El Niño/Southern Oscillation (ENSO, Manton *et al* 2001, Wang *et al* 2001, Mcbride *et al* 2003; Takahashi and Yasunari 2008, Zhou *et al* 2011, Ge *et al* 2017) and the Asian–Australian monsoon regime (He *et al* 1987, Matsumoto 1992, Webster *et al* 1998, Lau *et al* 2000, Wang *et al* 2000, Zhu 2018). Simulating the past and present climate over SEA is therefore a scientific challenge. It is also crucial for providing information on future changes in precipitation extremes that can be used by local governments to implement adaptation and mitigation.

Reliable projections are of great importance in projecting future climate change. The Coupled Model Intercomparison Project Phase 6 (CMIP6) uses the new scenarios, named Shared Socioeconomic Pathways (SSP), which are combined with the Representative Concentration Pathways (RCP) of CMIP5 (Eyring *et al* 2016). These new combinations enable several ways to examine the future projected changes in precipitation extremes over SEA. Current state-of-art climate models are more robust than previous CMIP ensembles and have shown the effective improvements in reproducing large-scale patterns of climate variables (Akinsanola *et al* 2020; Gusain *et al* 2020, Ha *et al* 2020, Jiang *et al* 2020, Wang *et al* 2020, Zhai *et al* 2020, Chen *et al* 2020b). However, to the best of our knowledge, there is still a lack of information regarding the projections of SEA precipitation extremes under the new CMIP6 scenarios. In this study, we aim to provide a comprehensive picture of the changing magnitude of precipitation extremes over SEA, and also to address the following questions: (a) How do the CMIP6 multi-models perform in simulating precipitation extremes over SEA? (b) What are the dominant roles of the projected precipitation extremes under CMIP6 scenarios in the long-term future?

2. Data and methods

2.1. Simulation data from the CMIP6 archive

The daily precipitation data are obtained from 15 CMIP6 model ensembles (table 1) for the first realization that are available at the time of initializing this study (up to August 2020). The future changes in precipitation extremes are projected under four SSP scenarios. For CMIP6, the four SSPs are categorized as SSP1-2.6 (sustainability), SSP2-4.5 (middle-of-the-road), SSP3-7.0 (regional rivalry) and SSP5-8.5 (fossil-fueled development) (O'Neill *et al* 2016). The historical simulations for the reference period of 1985–2014 are used in this study, while a future period of 2071–2100 is selected for the analysis of climate projection. The model outputs are interpolated to a regular geographical grid of 1° × 1°, consistent with the observational precipitation dataset introduced in the following subsection.

2.2. Observational data and index representation of extremes

The daily gridded precipitation data from the Southeast Asian Climate Assessment and Dataset (SACA&D) covering the period of 1981–2017 are used in this study. This high-resolution dataset with a resolution of 1° × 1°, called SA-OBSv2.0, has undergone strict quality control procedures, including data homogenization and time consistency, to improve reliability. SA-OBSv2.0 dataset includes several meteorological variables, such as daily precipitation amount, daily mean temperature, daily maximum temperature and daily minimum temperature. The

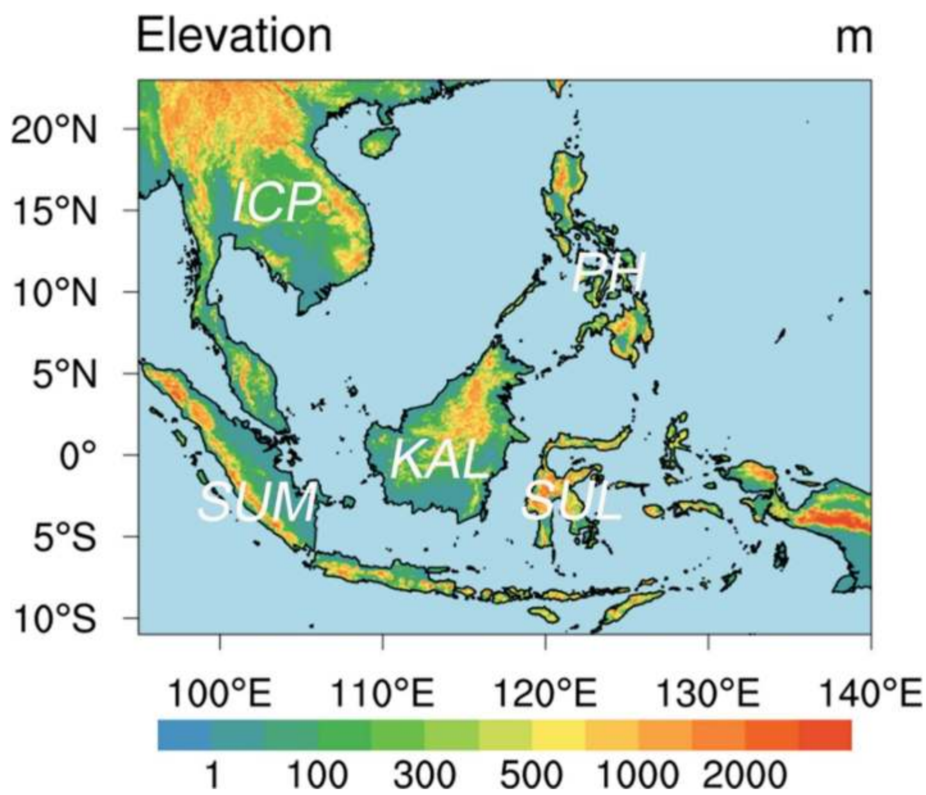

Figure 1. The orography (unit: m) of SEA and the geographical locations of the five main regions (ICP: Indochina Peninsula; PH: Philippines; SUM: Sumatra; KAL: Kalimantan; SUL: Sulawesi).

daily precipitation series are collected from the meteorological agencies of Australia, Indonesia, Malaysia, Philippines, Singapore, Thailand, and Vietnam. Additionally, precipitation series from the Global Historical Climate Network for American Samoa, Fiji, Kiribati, the Federated States of Micronesia, Papua New Guinea, Samoa, and the Solomon Islands are also involved (van den Besselaar *et al* 2017, Ge *et al* 2019a). As a result, 1393 rain gauge stations distributed over the whole SEA contribute to derive the SA-OBSv2.0 gridded dataset. We focus on the period of 1985–2014 to match the timescale of the CMIP6 historical runs. The SEA domain is located between 10° S to 23° N and 95° E to 140° E (figure 1) and comprises five subregions: the Indochina Peninsula (ICP; 6° N–23° N, 95° E–110° E), the Philippines (PH; 5° N–20° N, 118° E–130° E), Sumatra (SUM; 8° S–6° N, 95° E–108° E), Kalimantan (KAL; 4° S–6° N, 109° E–118° E) and Sulawesi (SUL; 6° S–3° N, 118° E–126° E).

Following the Expert Team on Climate Change Detection and Indices (ETCCDI, Zhang *et al* 2011, Sillmann *et al* 2013a, 2013b), six indices are selected to represent the precipitation extremes, as displayed in table 2. These are Rx1day (maximum consecutive 1 d precipitation), Rx5day (Maximum consecutive 5 d precipitation), SDII (Simple daily intensity), R20mm (very heavy precipitation days), CDD/CWD (Consecutive dry/wet days), PRCPTOT (Total precipitation of wet days) and R95pTOT (Precipitation of very wet days). More detailed information on the indices can be found on the ETCCDI website of http://etccdi.pacificclimate.org/indices.shtml.

2.3. Model performance metrics

The most common method to evaluate a climate model is the quantitative assessment of 'model-fit'; that is, how well the model results match observation-based data and results of other models or model versions. Here, we use the relative root mean squared error (RMSE′) and signal to noise ratio (SNR) to quantify the empirical accuracy and the robustness of the ensemble results, which have been shown skillful in climate projections and multi-model assessment (Han *et al* 2018, Ge *et al* 2019b).

Given the substantial uncertainties of projected changes in precipitation, the RMSE′ used to evaluate the climate simulation capability of each individual CMIP6 model is defined as follows (Gleckler *et al* 2008, Dong *et al* 2015). First, the RMSE is calculated for each model index with respect to the SA-OBS observations:

$$\mathrm{RMSE} = \sqrt{(X-Y)^2}.$$

With X being the model climatology of an extreme precipitation index and Y the corresponding index of the observation. All RMSEs are then used to derive the RMSE′ of each model:

$$\mathrm{RMSE}' = \left(\mathrm{RMSE} - \mathrm{RMSE}_{\mathrm{Median}}\right)/\mathrm{RMSE}_{\mathrm{Median}}$$

Table 2. List of the used extreme precipitation indices (recommended by the ETCCDI).

Label	Description	Index definition	Units
Rx1day	Maximum consecutive 1 d precipitation	Annual maximum consecutive 1 d precipitation	mm
Rx5day	Maximum consecutive 5 d precipitation	Annual maximum consecutive 5 d precipitation	mm
SDII	Simple daily intensity	The ratio of annual total precipitation to the number of wet days (⩾1 mm)	mm day^{-1}
R20mm	Very heavy precipitation days	Annual count of days when precipitation ⩾20 mm	days
CWD	Consecutive wet days	Maximum number of consecutive days when precipitation ⩾1 mm	days
CDD	Consecutive dry days	Maximum number of consecutive days when precipitation <1 mm	days
PRCPTOT	Total precipitation of wet days	Annual total precipitation from days ⩾1 mm	mm
R95pTOT	Very wet days precipitation	Annual total precipitation from days >95th percentile	mm

where $RMSE_{Median}$ is the ensemble median of all model RMSEs. Generally, a negative (positive) RMSE′ indicates a better (worse) performance than half (50%) of the models.

To express the credibility of the projection ensemble results, the SNR is defined as follows (Zhu et al 2020a):

$$SNR = |x_e| / \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - x_e)^2}$$

where x_i represents the variable or index simulated by an individual model, x_e denotes the corresponding ensemble result, and n is the ensemble size; the numerator and denominator refer to signal and noise, respectively. Therefore, SNR > 1 implies that signal is greater than noise, indicating relatively reliable projections.

3. Results

3.1. CMIP6 model validation

The RMSE′ of individual models in simulating precipitation extremes compared with the SA-OBS observations are summarized in figure 2. The results indicate that models vary considerably in their ability to simulate precipitation extremes. Three models, MPI-ESM1-2-HR, MPI-ESM1-2-LR and UKESM1-0-LL, perform fairly well with mainly negative RMSE′ values for different indices. The latest evaluation is consistent with our results, suggesting the MPI-ESM1-2-HR, MPI-ESM1-2-LR and UKESM1-0-LL could well capture the mean precipitation distributions over the SEA due to the reduced sea surface temperature biases (Pincus and Stevens 2013, Milinski et al 2016, Müller et al 2018, Sellar et al 2019). While FGOALS-g3 and IPSL-CM6A-LR show relatively weak performances because they overestimate the mean precipitation over the Maritime Continent (Boucher et al 2020, Li et al 2020). That is, the simulations are model-dependent and exhibit substantial uncertainty, which confirms the necessity of a model ensemble in investigating the climate simulations and projections.

The RMSE′ of the ensemble medians are shown in the last column of figure 2. The model ensemble median is chosen to represent the deterministic ensemble result rather than the mean value, to avoid results influenced by abnormally large model errors (outliers). It is demonstrated that the ensemble median results perform better than any individual models for all indices, which eliminates the structural model uncertainties to a great extent and so can be considered to reasonably represent the future projections in the study.

3.2. Projected changes in precipitation extremes

Figure 3 presents the projected changes of CMIP6 ensemble medians of precipitation-based indices over SEA during the long-term future at the end of the 21st century (2071–2100). Most of the extreme precipitation indices (i.e. Rx1day, Rx5day, SDII, R20mm and R95pTOT) increase significantly across the ICP and Maritime Continent for all scenarios. However, for the SSP1-2.6 scenario, decreases in CDD are combined with the increases in CWD and SDII over parts of ICP, indicating a generally wetter future in this region. The opposite patterns in CDD and CWD are projected over the Maritime Continent in this scenario, while the other four indices show prominent increases, especially over SUM and KAL. This non-uniform phenomenon suggests the intensification of both wet and dry conditions over SEA, which is consistent with the earlier projected changes in CMIP5 under the RCP 2.6 scenario (Sillmann et al 2013b). The pronounced increase of total precipitation of wet days (PRCPTOT) is projected over most of SEA under all SSP scenarios. Over some regions of the southern SUM, the projected changes show decreases under

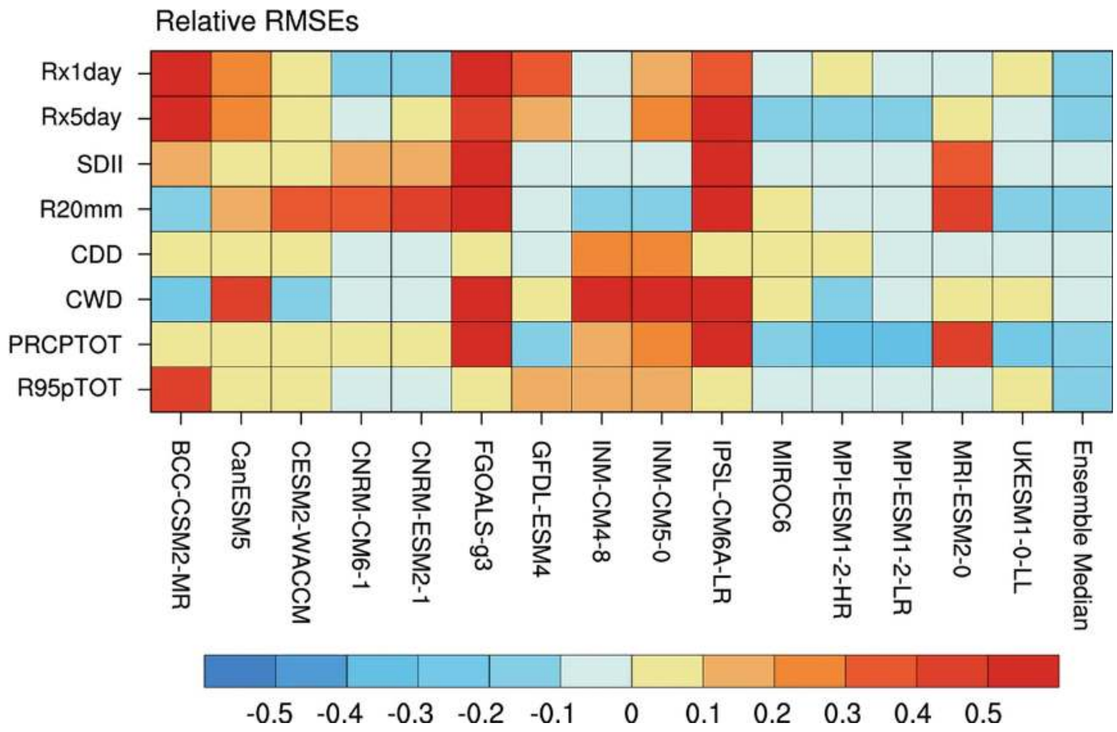

Figure 2. Portrait diagram of relative RMSEs (RMSE′) of precipitation extreme indices simulated by CMIP6 models versus the observation data during the period of 1985–2014.

the SP3-7.0, and SSP5-8.5 scenarios, however, the decreasing signals are mostly not significant. This is in agreement with the projected changes for the end of 21st century in the CMIP5 GCMs ensemble, suggesting the decreasing tendency over the southern SUM in total precipitation under both RCP4.5 and RCP8.5 scenarios (Kang *et al* 2018, Giorgi *et al* 2019, Supari *et al* 2020). Reduced PRCPTOT is consistent with the increased CDD over southern SUM, while indices of extremes frequency (R20mm) and extremes intensity (Rx5day and SDII) show a significant and robust increase over the entire SEA, implying a potential risk of intensified precipitation extremes in natural ecosystems under the accelerated emission scenarios.

Compared with the SSP1-2.6 scenario, more pronounced increases in Rx1day, Rx5day, SDII, R20mm and R95pTOT are projected over all of SEA under the SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios. In addition, it is noteworthy that spatial patterns of CDD and CWD have gradually extended northward to the ICP from lower- to higher-emission scenarios. Larger high-confidence areas of increasing CDD (decreasing CWD) can be particularly observed under the SSP3-7.0 and SSP5-8.5 scenarios. This spatial evolution implies more heavy and extreme precipitation events (Rx5day, R20mm and SDII) are expected to occur with increased emissions, and extended dry spells (CDD) and shortened wet spells (CWD) could be mainly attributed to enhanced locally heavy rainfall over a short time scale.

Generally, precipitation extremes are becoming more intense over SEA which is supported by future projections from CORDEX climate model ensembles (Ge *et al* 2019b). This suggests that increases in extreme precipitation are closely related to enhanced tropical convective precipitation, further concentrating rainfall in a very short period over SEA. This would have critical impacts on local water resources, food security, agricultural production etc, especially for those developing countries with large coastal population densities.

3.3. Dominant roles of precipitation extremes in different scenarios

To identify the regional response to the different scenarios, we highlight here the CMIP6 projected percentage changes in precipitation extremes (averaged over the land area within SEA) in figure 4. In general, the CMIP6 models exhibit a distinctly large spread in different scenarios. However, it is notable that the ensemble medians of the index changes are all greater than 0 except CWD, implying increasing trends of precipitation extremes compared with the reference period of 1985–2014.

The most significant increases in R20mm and R95pTOT are projected with magnitudes of 22% and 102% for the SSP5-8.5 scenario (figures 4(a) and (h)), while the ensemble median changes of Rx5day and SDII show consistent increases, with magnitudes of 16% and 11%, respectively (figures 4(b) and (c)). The increasing magnitudes of Rx1day range from 7% (SSP1-2.6) to 21% (SSP5-8.5) and PRCPTOT shows a similar increase with the magnitude about 4% in SSP1-2.6, SSP2-4.5 and SSP3-7.0 scenarios, but

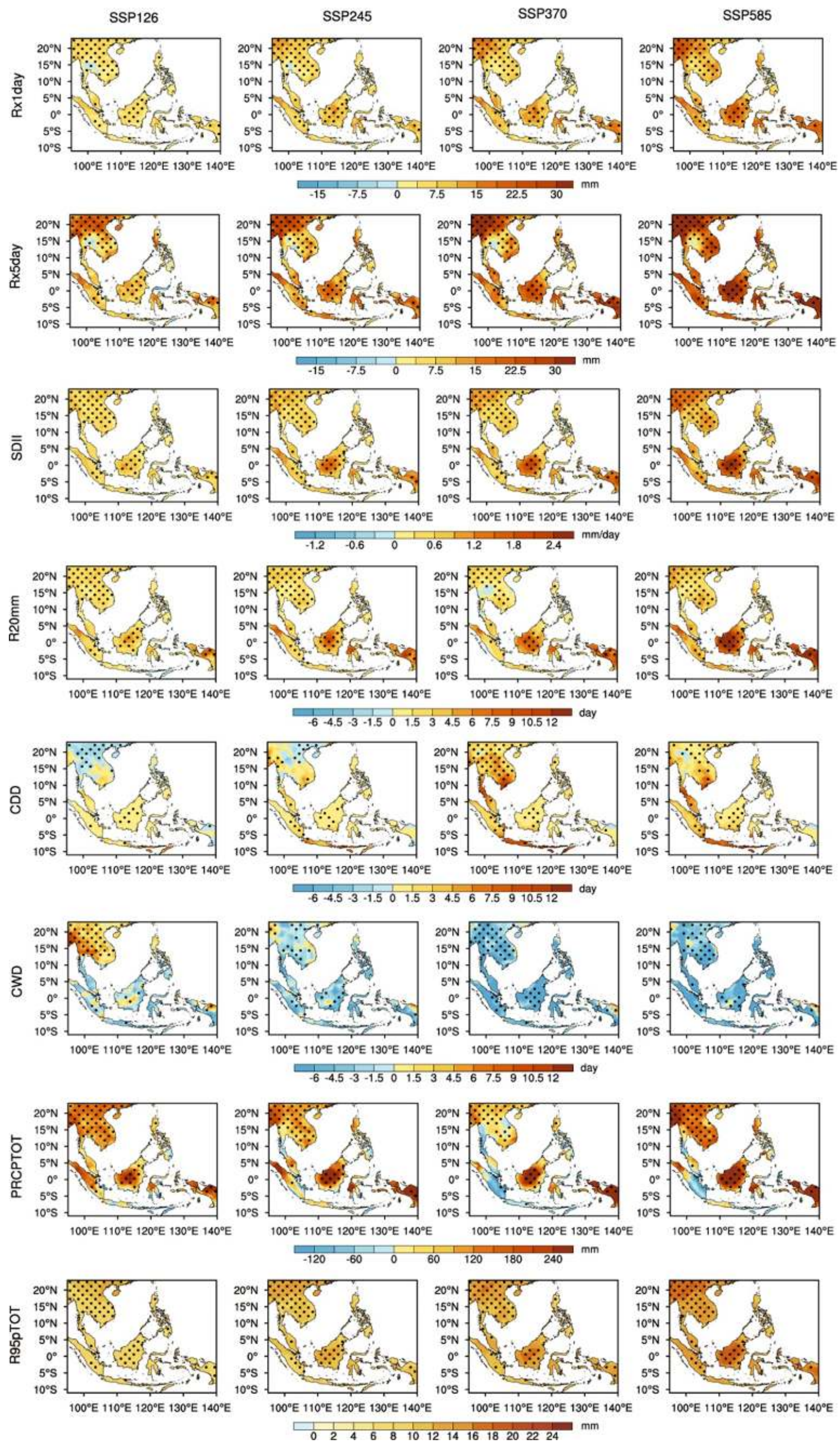

Figure 3. Projected CMIP6 ensemble median changes in precipitation extreme indices during 2071–2100 under the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, relative to the climatology in 1985–2014. The black dots indicate where at least two-thirds of the models agree on the sign of change. All SNRs are greater than 1 over the area.

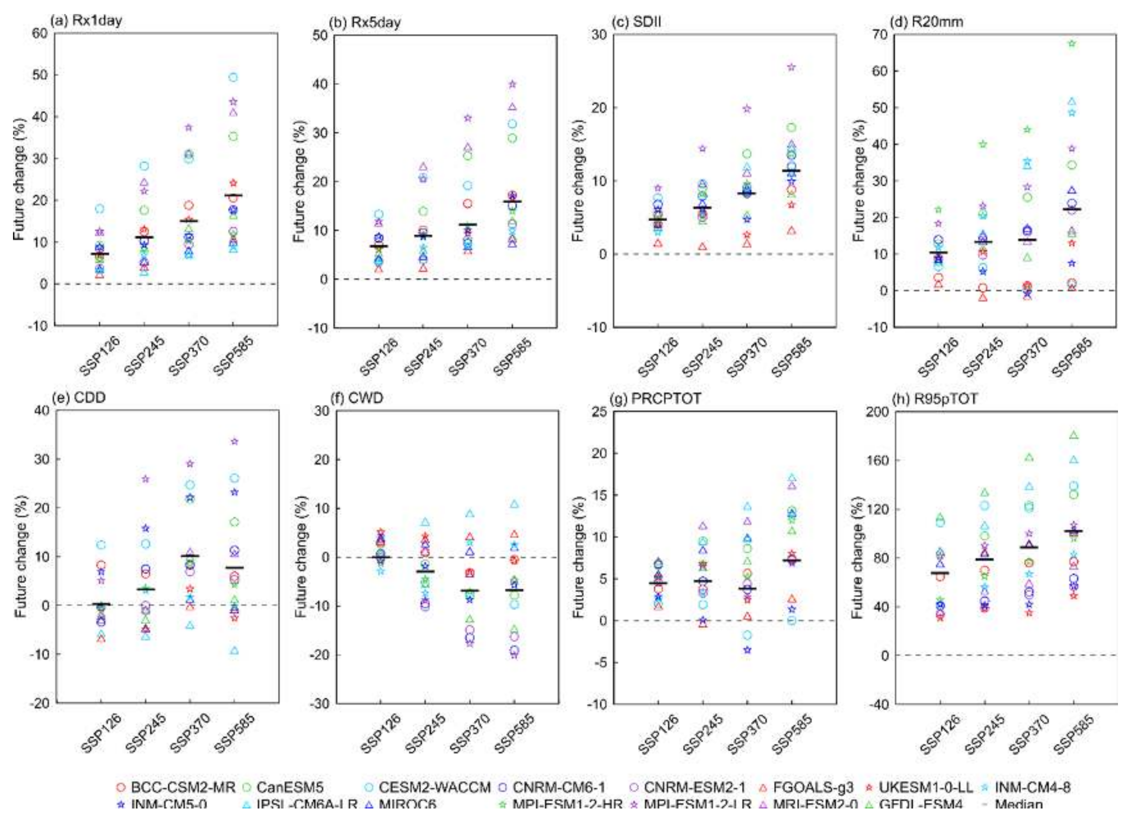

Figure 4. Projected changes (unit: %) in percentage of precipitation extreme indices (2071–2100 minus 1985–2014). The black line indicates the ensemble median of 15 models over SEA.

is 7% in SSP5-8.5. On the other hand, the projected changes in CDD and CWD are nearly 0 under SSP1-2.6 scenario. However, CDD is projected to increase by 3%, 10% and 8% under the scenarios of SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively, whereas the CWD is suggested to experience a pronounced decrease by −3% in SSP2-4.5 and by −7% in SSP3-7.0 and SSP5-8.5. In addition, we noticed that the non-uniform spatial patterns in CDD and CWD are projected under the SSP1-2.6 and SSP2-4.5 scenarios. To examine the climate responses to the lower GHG emission scenarios in more regional details, percentage changes of these two indices averaged over each subregion are presented in figure 5. The ensemble median changes in CDD indicate an increase over the PH, SUM and KAL, with magnitudes of 3%, 10% and 8% under the SSP1-2.6 scenario, while CWD shows a slight decrease over the SUM, KAL and SUL by −2%, −1% and −4%, respectively. For projections under the SSP-4.5 or higher emission scenario, CDD indicates consistent increases over the subregions, while it shows the reversed case for CWD. It implies that almost the entire area would be characterized by a moderate change under the lower GHG emissions, suggesting the importance of keeping the sustainability pathway for climate stabilization. By contrast, with the enhanced GHG pathways, the significant increase of R20mm and SDII suggest that wet days become wetter and intensified precipitation events more likely to occur frequently at the end of the 21st century, emphasizing that daily precipitation intensity tends to increase more abruptly than mean precipitation over the land area in SEA under a warmer future.

4. Conclusions and discussion

In this study, we have investigated future changes in precipitation extremes over SEA under four scenarios using current CMIP6 models. The results provide latest information on the climate responses of SEA to different emission scenarios at the end of the 21st century. The major findings are summarized as follows:

(a) Precipitation indices of Rx1day, Rx5day, SDII, R20mm and R95pTOT show consistent increases across the ICP and Maritime Continent under the four CMIP6 scenarios. Changes in annual total precipitation (PRCPTOT) indicate a general increase over SEA, except over the southern SUM under the SSP3-7.0 and SSP5-8.5 scenarios. Projected changes in most of the indices are more significant under higher emissions than under the lower-emission scenarios. On the other hand, the spatial evolution of CDD and CWD reveals that extended dry spells concurrent with shortened wet spells will gradually appear over SEA with rapidly rising emissions.

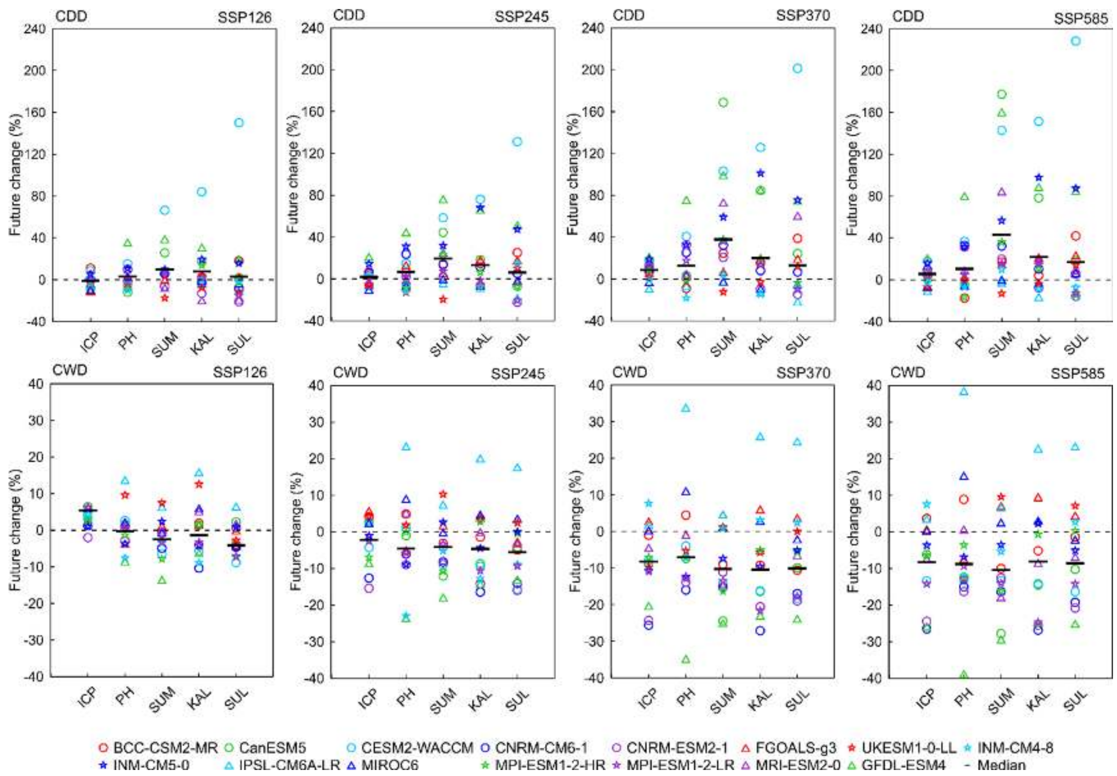

Figure 5. Projected changes (unit: %) in percentage of CDD and CWD averaged over each subregion of SEA (2071–2100 minus 1985–2014). The black line indicates the ensemble median of 15 models over each subregion.

(b) It is evident that the global mean temperature warming will increase the occurrence of precipitation extremes in the future. The precipitation over SEA is projected to be enhanced, while persistent increases would mainly concentrate on the tropical islands, suggesting the high sensitivity of the precipitation extremes to the GHG emissions. Most of the CMIP6 ensemble models agree with the sign of change, with SNRs all greater than 1, although they exhibit a relatively large spread in precipitation extremes.

(c) The averaged median changes of indices vary considerably under different scenarios over SEA. The most pronounced increases are projected in R20mm and R95pTOT, with magnitudes of 22% and 102% under the SSP5-8.5 scenario, while the changes in CWD are projected to decrease, with the magnitude of −7% in SSP3-7.0 and SSP5-8.5 scenarios. The indices' evolutions indicate an intense increase in extreme precipitation events over this region in a warmer future.

The SEA climate is strongly affected by the tropical monsoon regime, and has been the subjected of increasing concern due to the high climate stresses of its exposure to global warming. Future projections in monsoon rainfall from CMIP3 to CMIP6 scenarios show its intensification over the Asian region, with a corresponding rise in precipitation extremes, which has many implications for ecological impacts and social risk throughout SEA (Scoccimarro *et al* 2013, Zhou *et al* 2014, Qi *et al* 2016, Zhang *et al* 2018, Chen *et al* 2020b, Grose *et al* 2020, Narsey *et al* 2020, Scoccimarro and Gualdi 2020). It is very disappointing that limiting warming to 1.5 °C seems to be barely feasible, although in fact the Paris Agreement target remains possible and could be attainable with ambitious and immediate action (Smith *et al* 2019). Based on our results from CMIP6, we again emphasize the necessity of restricting global warming for the mitigation of climate extremes in the countries in SEA. Further possible efforts should never be ignored and prompting actions would never be untimely.

In addition, any subsequent research should not only be conducted in terms of the frequency and intensity of climate extremes, but should also consider population exposure and local vulnerability (Chen and Sun 2019, Chen *et al* 2020a). More work remains necessarily to be conducted on comparisons between model ensembles with and without bias correction (Maraun *et al* 2017, Guo *et al* 2018, Sun *et al* 2019). High-resolution convection- permitting models and the new generation of CORDEX experiment design for the dynamical downscaling of CMIP6 are fundamental for quantifying and assessing changes of climatological means, variability and extremes. In conclusion, some evidence has been shown in our present study using the currently released archive compared with the previous generation, which provides credible findings for regionally relevant climate change projections over SEA. However, we suggest that this result should be further examined as more models are added, since full CMIP6 models will be available in the near future and understanding the response to different global warming threshold is essential for eliminating the uncertainties in SEA climate projections.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://esgf-node.llnl.gov/projects/cmip6/.

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