SouthEast Asia HydrO-meteorological droughT (SEA-HOT) framework: A case study in the Kelantan River Basin, Malaysia

Mou Leong Tan[a,*], Liew Juneng[b], Fredolin T. Tangang[b], Narimah Samat[a], Ngai Weng Chan[a], Zulkifli Yusop[c], Sheau Tieh Ngai[d]

[a] Geography Section, School of Humanities, Universiti Sains Malaysia, 11800 Penang, Malaysia
[b] Department of Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[c] Centre for Environmental Sustainability and Water Security, Universiti Teknologi Malaysia, Skudai 81310, Malaysia
[d] School of Atmospheric Sciences, Sun Yat-Sen University, Tangjiawan Zhuhai, Guongdong province, China.

ARTICLE INFO

ABSTRACT

A holistic framework was introduced to project the potential hydro-meteorological droughts of the Kelantan River basin, Malaysia. The framework integrates the multi-model high-resolution climate projections of the Coordinated Regional Climate Downscaling Experiment – Southeast Asia (CORDEX-SEA) and the widely applied Soil and Water Assessment Tool (SWAT) model. The quantile mapping approach was used to reduce the biases in the CORDEX-SEA projections before applying into SWAT. The SWAT-simulated standardized streamflow index (SSI) was validated with observed data to check the capability of SWAT in drought estimation. The result indicated that SWAT was able to reproduce the historical 1982, 1987 and 1997–1998 droughts and simulate SSI from one to twelve-month scales well, with the NSE and R^2 values of 0.74–0.79 and 0.76–0.80, respectively. Overall, the annual precipitation, maximum and minimum temperatures are projected to change from -8.19 to 13.11% (-13.35 to 10.10%), 0.45 to 2.41 °C (0.43 to 3.99 °C) and 0.73 to 2.98 °C (0.70 to 4.69 °C), respectively, by the end of the 21st century under the RCP4.5 (RCP8.5) scenario. This would cause the future annual streamflow to vary from -10.37 to 31.09% and -19.87 to 13.24% under RCP4.5 and RCP8.5, respectively, with the reductions are mainly found in the north-western region of the basin. Monthly precipitation and streamflow would be likely to decrease in January and February and increase in September. Robust evidence shows that the meteorological drought duration is likely to become longer in the 2081–2100 period under RCP4.5. Meanwhile, there is not enough evidence to claim that hydrological drought will become more significant in the near future.

1. Introduction

The population of Southeast Asia had increased from 165 million in 1950 to 662 million in 2019, and accounted for about 8.5% of the world's population (UN, 2019). Droughts have regularly destroyed crops, caused forest fire and reduced water resources in many regions of Southeast Asia. There have been 52 drought events affecting more than 77 million people in Southeast Asia since 1996 according to the International Disaster Database (EM-DAT, 2019). Meanwhile, the Association of Southeast Asian Nations (ASEAN) Disaster Information Network (ADInet, 2019), which is under the ASEAN Coordinating Centre for Humanitarian Assistance on disaster management (AHA) reported 42 drought events in Southeast Asia from 2012 to 2019. Unlike flood, the onset and end of a drought event are very difficult to identify, causing many drought events to go unreported. Therefore, the actual number of drought events in Southeast Asia might be higher than those reported in both the EM-DAT and AHA databases.

To reduce the drought impact in Southeast Asia, the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) and ASEAN have proposed three priority areas: (1) drought risk assessment and early warning system improvement, (2) foster drought risk financing markets, and (3) drought adaptation capabilities enhancement (UN and ASEAN, 2019). Understanding hydro-meteorological drought patterns at the basin scale is important to achieve these three targets. However, hydro-meteorological drought assessment is limited in Southeast Asia due to the lack of expertise, funding, reliable data and a

proper assessment framework. Therefore, developing of a standardized and comprehensive hydro-meteorological drought assessment framework specifically designed for Southeast Asia is urgently needed to improve the formulation of drought adaptation strategies to increase community resilience against drought. Hydro-meteorological drought modelling under climate change scenarios, with a combination of multiple General Circulation Models (GCMs), hydrological models and drought indices are commonly used to study drought (Mishra and Singh, 2011; Oguntunde et al., 2017). However, due to the typically coarse resolutions of GCMs (100–300 km), the outputs need to be downscaled for local or basin scale applications. In general, GCMs outputs are downscaled either dynamically or statistically to the local scale before applying in a calibrated hydrological model (Singh et al., 2019). Projected hydro-meteorological patterns are then converted into various drought indices to quantify potential future droughts in terms of number of events, duration and intensity. In Southeast Asia, the Co-ordinated Regional Climate Downscaling Experiment – Southeast Asia (CORDEX-SEA) has been implemented to provide multi-model and high-resolution climate change scenarios (Juneng et al., 2016; Ngo-Duc et al., 2017; Supari et al., 2020; Tangang et al., 2020; Tangang et al., 2019; Tangang et al., 2018).

Most of the drought studies in Southeast Asia focused solely on meteorological drought assessment (Bong and Richard, 2020; Thilakarathne and Sridhar, 2017; Wichitarapongsakun et al., 2016). Consideration of both the hydrological and meteorological droughts is relatively rare in Southeast Asia, where only a few studies can be found in Vietnam (Sam et al., 2019; Vu et al., 2017) and Malaysia (Tan et al., 2019a). Vu et al. (2015) applied three regionally downscaled GCMs to the Soil and Water Assessment Tool (SWAT) model in the Central Highland region of Vietnam to study hydro-meteorological droughts in a small tributary of the Mekong River and concluded that the number of drought events likely to increase in the future but at a lower intensity. In Malaysia, Tan et al. (2019b) assessed future hydro-meteorological droughts of the Johor River Basin (JRB), which supplies fresh water to the populations of southern Peninsular Malaysia and Singapore. The CORDEX-SEA climate projections were incorporated into SWAT to simulate future streamflow for Standardized Streamflow Index (SSI) calculations. However, the accuracy of the SWAT-simulated streamflow in calculating SSI has not been well studied. This remains as a gap in the existing literature, including the general hydro-meteorological droughts modelling framework.

This study aims to assess the potential frequency, intensity and duration of hydro-meteorological droughts in the Kelantan River Basin (KRB) adopting a new comprehensive framework which is customized for the Southeast Asia region, namely the SouthEast Asia HydrO-meteorological droughT (SEA-HOT). It integrates the latest CORDEX-SEA projections with SWAT for assessing the characteristics of future hydro-meteorological droughts. Since CORDEX-SEA covers the entire Southeast Asia, this study serves as an example of future hydro-meteorological droughts assessment and can be repeated in any basin in the region. In a long run, SEA-HOT helps to strengthen the formulation of scientific-based drought policy and adaptation strategies in Southeast Asia. In the case of KRB, major contributions of this study include (1) the development of a more comprehensive and up-to-date hydro-meteorological droughts modelling framework, (2) validation of the SWAT-based SSI, and (3) increasing the understanding of local hydro-meteorological droughts changes in Southeast Asia.

2. Materials and methods

2.1. Kelantan River Basin

Kelantan River Basin (KRB) is located in the northeast region of Peninsular Malaysia, as shown in Fig. 1. The basin has a total area of 12,685 km^2, which constitutes approximately 85% of the Kelantan state. KRB is mainly covered by tropical rainforest, followed by rubber

and oil palm plantations (Tan et al., 2018b). Mountainous areas dominate in the west and southwestern regions, with elevation ranging from −2 m to 2174 m. As a tropical basin, it receives a high precipitation amount, particularly during the wet phase of the northeast monsoon (NEM) season from November to January (Tan et al., 2017b). Meanwhile, drought normally occurs from January to March as it receives less precipitation when the monsoon trough is located further south over Java (Tangang et al., 2012). The average maximum, mean and minimum temperatures of the basin are around 32, 27 and 22 °C, respectively. The KRB was selected as the test site due to the availability of good quality and well-distributed observations. In addition, many studies have proven that SWAT can simulate streamflow satisfactorily in this basin (Tan et al., 2017c; Tan et al., 2018b).

2.2. CORDEX-SEA

To assess the impact of climate change on the variation of hydrological characteristics over a catchment, a local projection of future climate scenarios is required. At the global scale, general circulation models (GCMs) are the main tools used to produce such information, as bounded by different possible scenarios of greenhouse gases emission. Globally, the projection is made available from the IPCC's Coupled Model Intercomparison Project (CMIP) (Knutti and Sedláček, 2013; Taylor et al., 2012). However, the GCMs typically operate at 100–300 km resolution and do not simulate regional and local processes appropriately. A downscaling driven by the GCMs projection is, therefore, required to produce high-resolution projections for specific regions of interest. Although statistical downscaling approaches are relatively simple and fast, the dynamic downscaling with regional climate models (RCMs) is generally more favorable as it produces more physically consistent with regional climatic variables and adds fine-scale information in addition to that already provided by the GCMs (Rummukainen, 2016).

In view of the expensive computation required for RCMs simulations, a more coordinated framework is needed to generate the large ensemble of regionally downscaled projections for better uncertainty quantifications. The Coordinated Regional Downscaling Experiment (CORDEX) is a framework by the World Climate Research Program (WCRP) under the World Meteorological Organization (WMO) to coordinate and facilitate the cross-region challenges of regional climate modelling (Giorgi et al., 2009). The downscaled projection output from CORDEX has been used extensively to drive different impact models for comprehensive regional impact assessment in many parts of the world in different contexts and sectors including agriculture (Dubey and Sharma, 2018), hydrology and water resources (Marchane et al., 2017), extreme storms surge and winds (Brázdil et al., 2019), heat and health (Chi et al., 2019) and air quality (Lacressonnière et al., 2016), etc.

Currently, downscaling experiments of CORDEX's projection have been conducted over most of the land area on the globe covered by 14 different CORDEX domains (www.cordex.org). CORDEX-SEA consists of a set of dynamically downscaled high-resolution regional climate projections (25 km × 25 km) from multiple Coupled Model Intercomparison Project Phase 5 (CMIP5) GCMs for the Southeast Asia domain (Tangang et al., 2020). The main purpose of the CORDEX-SEA development is to improve simulations of regional climate conditions for a better understanding of the potential climate extremes in the future in SEA. More information on CORDEX-SEA is available on the developers' website at http://www.ukm.edu.my/seaclid-cordex/.

A total of 4 downscaled climate projections under the Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios for three future periods (2016–2035, 2046–2065 and 2081–2100) as listed in Table 1, were chosen from the CORDEX-SEA data archive for use in the current study. These 24 climate projections were mainly produced from a combination of four GCM-RCMs: (1) MPI-ESM from the Max Planck Institute for Meteorology Germany with Regional Climate Model version 4.3 (RegCM4); (2) CNRM-CM5 from the French National Centre
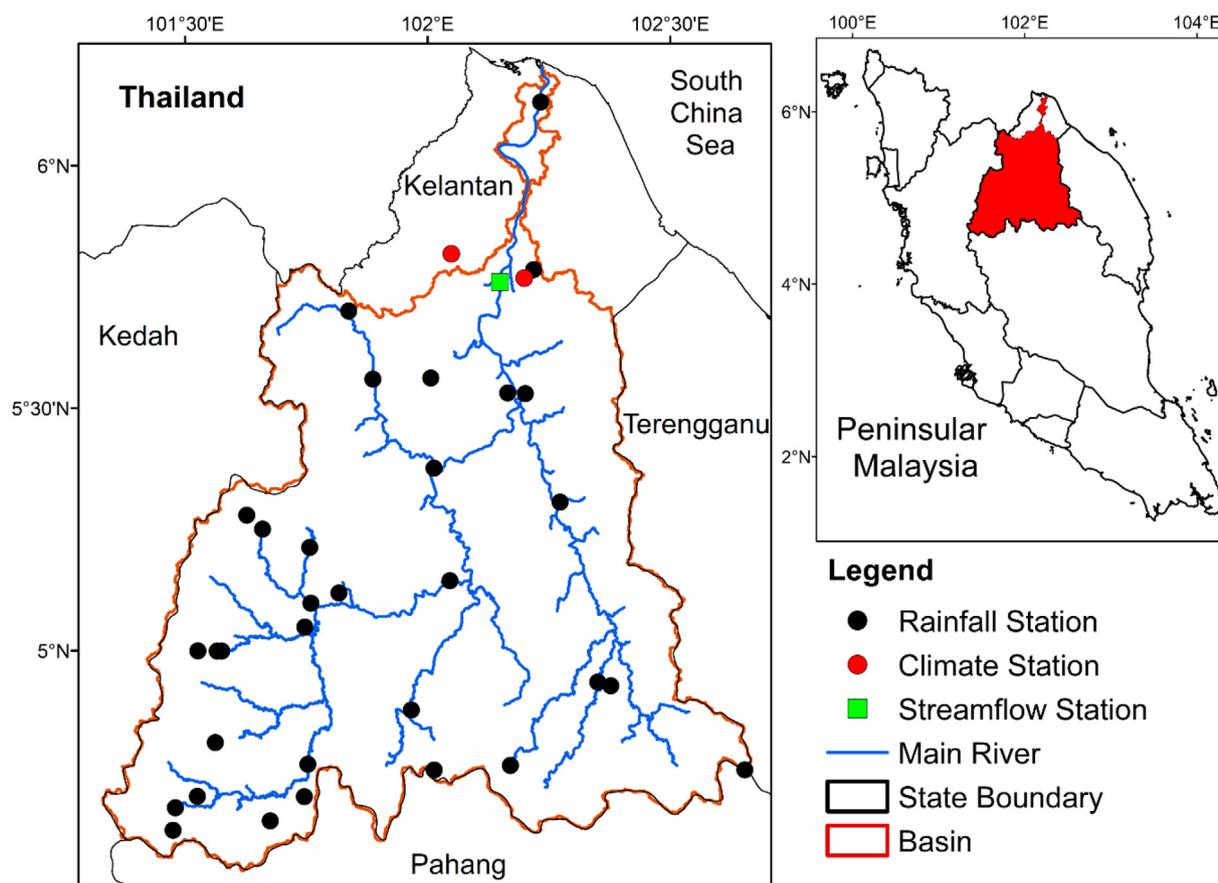
Fig. 1. Kelantan River Basin, Malaysia.

for Meteorological Research with RegCM4; (3) ECEarth GCM from the Europe-wide consortium with RegCM4; and (4) CSIROMk3–6-0 from the Commonwealth Scientific and Industrial Research Organization, Australia with Rossby Centre downscaled with RCA4).

2.3. SWAT input

The basic input data to set up a SWAT model includes a Digital Elevation Model (DEM), land use map, soil map, daily precipitation, and daily maximum and minimum temperatures. The Shuttle Radar Topography Mission (SRTM) 90 m DEM produced by the National Aeronautics and Space Administration (NASA) was used for basin de-lineation and river network formation. Land use and soil maps were scanned and collected from the Ministry of Agriculture and Agro-based Industry Malaysia (MOA). The scanned maps were digitized and con-verted into the digital format required for SWAT setup. Meanwhile, daily precipitation and maximum and minimum temperature data from 1980 to 2004 were provided by the Malaysian Meteorological Department (MMD). Additional daily precipitation and monthly streamflow data were supplied by the Department of Irrigation and Drainage (DID) Malaysia.

2.4. SEA-HOT framework

SEA-HOT is divided into four major phases: (1) SWAT model setup, calibration and validation; (2) comparing and bias correcting CORDEX-SEA; (3) incorporating bias-corrected CORDEX-SEA projections into calibrated SWAT and (4) hydro-meteorological drought assessment in the aspects of number, intensity and duration, as shown in Fig. 2. The proposed SEA-HOT framework concept is basically an improvement of the previous hydro-meteorological drought studies in Southeast Asia (Tan et al., 2019b; Vu et al., 2015; Vu et al., 2017). Application of the latest CORDEX-SEA projections and the SWAT-based SSI validation are expected to improve the assessment of potential hydro-meteorological droughts in Southeast Asia. The framework will be explained further in the next four sub-sections.

2.4.1. SWAT modelling

SWAT is a popular eco-hydrological model developed under colla-boration between Texas A&M University and the United States Department of Agriculture to evaluate the impact of land management on water (Arnold et al., 1998). It is a time-continuous, semi-distributed and physical-based model that can simulate hydrological processes and water quality in small watersheds and river basins. The major
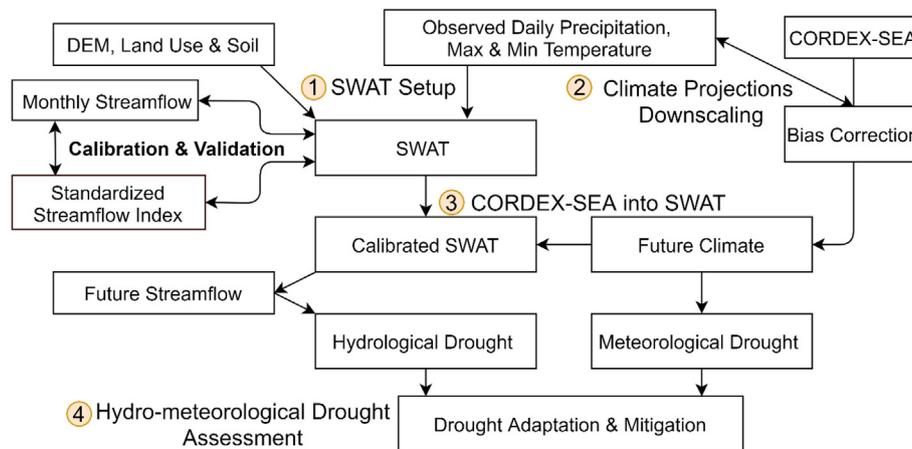
Table 1
Climate Scenarios.

Driving GCM	RCM	RCP	Period	Symbol
MPI-ESM	REGCM4	4.5, 8.5	2016–2035, 2046–2065, 2081–2100	REGCM4MPI
CNRM-CM5	RCA4	4.5, 8.5	2016–2035, 2046–2065, 2081–2100	RCA4CNRM
CSIROMk3–6-0	REGCM4	4.5, 8.5	2016–2035, 2046–2065, 2081–2100	REGCM4CSIRO
ECEarth	REGCM4	4.5, 8.5	2016–2035, 2046–2065, 2081–2100	REGCM4ECEarth

Fig. 2. SouthEast Asia HydrO-meteorological droughT (SEA-HOT) Framework.

advantages of SWAT are availability to the public, continuous improvement by the developer, an abundance of online teaching resources, an active user community and well-organized workshops. More information on SWAT applications, research direction and historical and recent development can be found in various articles and reviews (Arnold et al., 2012; Bieger et al., 2017; Gassman et al., 2007; Tan et al., 2019b). SWAT is applicable and reliable for application in Southeast Asia, where the reported NSE values in calibration and validation were mostly above 0.7 (Tan et al., 2019b). Climate change-related study is a major SWAT application in Southeast Asia but it is mainly limited to general streamflow assessments. The development of the SEA-HOT framework could promote the use of SWAT in extreme drought evaluations, which is helpful for local authorities to design more effective adaptation strategies.

SWAT development can be divided into five parts: (1) basin delineation and river network formation using DEM; (2) the addition of land use, soil and slope information to create hydrologic response units (HRUs); (3) incorporating observed daily precipitation and maximum and minimum temperatures into SWAT; (4) initial running and checking of SWAT; and (5) parameter sensitivity analysis, calibration and validation. A minimum threshold value of 10,000 ha was assigned for the smallest sub-basin formation, which resulted in a total of 81 sub-basins. The HRU threshold for land use, soil and slope were all set as 10%, to improve computational efficiency. The final phase was conducted using the semi-automated Sequential Uncertainty Fitting algorithm (SUFI-2) approach within the SWAT Calibration and Uncertainty Tool (SWAT-CUP) (Abbaspour et al., 2007). Two commonly used statistical approaches, Nash-Sutcliffe Efficiency (NSE) and coefficient of determination (R^2), were applied to test the capability of SWAT in simulating streamflow in both the calibration and validation periods. According to Moriasi et al. (2015), SWAT can be judged "satisfactory" if NSE > 0.5 and R^2 > 0.6, "good" if NSE > 0.7 and R^2 > 0.75, and "very good" if NSE > 0.8 and R^2 > 0.85.

2.4.2. CORDEX-SEA bias correction

Basin-scale precipitation spatial variability could be better captured using RCM compared to GCM (Lee et al., 2019), especially in tropical regions with high orographic precipitation. However, the characteristics of daily precipitation projected by RCM often do not match well with observed data in terms of distribution, sequencing and magnitude (Charles et al., 2019). Such biases can be due to the systematic errors in the models associated with physical parameterizations in the model (Tangang et al., 2020). Hence, bias correction is essential to adjust RCM projections to match certain observation characteristics before application to the hydrological model.

In this study, the quantile mapping (QM) approach, which is widely applied in hydrology studies (Roy et al., 2018; Shrestha et al., 2017),

was selected to correct the RCM projections (Table 1). QM uses a transfer function to adjust the RCM quantiles to match the observation quantiles for both the precipitation and temperature data (Shrestha et al., 2017). Ngai et al. (2020) developed an empirical quantile distribution-based algorithm to adjust the biases of both GCMs and RCMs over Southeast Asia. The improved QM formula was computed as follows:

$$F_r = \frac{P_{obs}(r)}{P_{sim}(r)} \tag{1}$$

$$P'_{sim} = F(r) \times P_{sim}(r) \tag{2}$$

$$F_r = T_{obs}(r) - T_{sim}(r) \tag{3}$$

$$T'_{sim}(r) = F_r \times T_{sim}(r) \tag{4}$$

where F is the adjustment factor, r is the rth quantile, P_{obs} is observed precipitation, T_{obs} is observed temperature, P_{sim} is the RCM precipitation projection, P_{sim} is the RCM temperature projection, P'_{sim} is the bias-corrected RCM precipitation projection and T'_{sim} is the bias-corrected RCM temperature projection. Detailed information on the quantile mapping bias correction scheme for CORDEX-SEA is available in research articles by Tan et al. (2019b) and Ngai et al. (2020).

2.4.3. Incorporation of CORDEX-SEA to SWAT

As mentioned earlier, RCP4.5 and RCP8.5 were selected to understand the possible changes under moderate and no adaptation strategies, respectively, in tackling climate change issues. In RCP4.5, greenhouse gas (GHG) emissions rise steadily from 2010, reach a peak at around 2040, and then decline slowly until the end of the 21st century. Meanwhile, GHG emissions in RCP8.5 continue to increase throughout the 21st century. Quantification of future precipitation, temperature and hydro-meteorological drought changes for the periods of near (2016–2035), middle (2046–2065) and late (2081–2100) 21st century relative to the baseline (1986–2005) under both the RCP scenarios were conducted. Hence, a total of four bias-corrected historical and 24 bias-corrected future RCM projections under RCP4.5 and 8.5 were incorporated into the calibrated SWAT model. This is carried out by replacing the pcp1.pcp and tmp1.tmp climate files (observations) that are available in the calibrated SWAT folder with the new bias-corrected pcp1.pcp and tmp1.tmp climate files. The bias-corrected climate files can be generated using the ArcSWAT weather input function. The SWAT.exe application file was re-run with the new bias-corrected climate files to simulate the future streamflow projections.

2.4.4. Hydro-meteorological drought assessment

Standardized precipitation index (SPI) is a widely accepted and preferred index due to its simplicity and because it requires only

Table 2
SPI and SSI Classification.

Index value	Class
SPI or SSI ≥ 2	Extremely wet
$1.5 \leq$ SPI or SSI < 2	Very wet
$1 \leq$ SPI or SSI < 1.5	Moderately wet
$-1 <$ SPI or SSI < 1	Normal conditions
$-1.5 <$ SPI or SSI ≤ 1	Moderately dry
$-2 <$ SPI or SSI ≤ -1.5	Very dry
SPI or SSI ≤ -2	Extremely dry

monthly precipitation data. SPI was formulated by McKee (1993) to quantify meteorological drought for different time scales, ranging from 1 to 48 months. While, SSI is statistically similar to SPI, it uses monthly streamflow as input data. SSI is defined as the difference of streamflow from mean divided by the standard deviation (Khatiwada and Pandey, 2019). In this study, SPI and SSI were computed using the CORDEX-SEA and SWAT-simulated streamflow, respectively, using the R programming tool. Table 2 illustrates the SPI and SSI classification scheme, where the climate condition is considered as moderately dry, very dry and extremely dry with the index values less than -1, -1.5 and -2, respectively.

Assessment of SWAT on extreme flow simulations is still relatively limited in the literature (Tan et al., 2020). To the best of our knowledge, the performance criteria for SWAT-simulated SSI is yet to be reported. Hence, the streamflow performance recommendation (Moriasi et al., 2015) that is mentioned in Section 3.2 was used as the SSI performance rating. For example, the SWAT-based SSI simulation is considered as "good" if NSE and R^2 are more than 0.7 and 0.75, respectively. A drought event was defined as when the SPI/SSI < -1 for at least three consecutive months, accompanied by other drought parameters including the drought frequency, intensity and duration. Drought frequency is the number of drought events for each evaluation period (i.e. 2016–2035). Meanwhile, drought duration and intensity are described as the longest duration and the lowest index value in an evaluation period, respectively.

3. Results & discussion

3.1. SWAT capability assessment

The capability of SWAT in KRB has been well proven and reported in many previous studies (Tan et al., 2017c; Tan et al., 2018a; Tan et al., 2018b; Tan and Yang, 2020). Similarly, the baseflow alpha-factor (ALPHA_BF), SCS runoff curve number (CN2) and groundwater "revap" coefficient (GW_REVAP) are among the most sensitive parameters of SWAT calibration in KRB. The range and final fitted value of SWAT parameters can be found in Table 3. As shown in Table 4 and Fig. 3, the SWAT model can simulate monthly streamflow well during all the three

Table 3
SWAT Calibration parameters.

Parameter_Name	Min_value	Max_value	Fitted_Value
1:V_CN2.mgt	35.00	98.00	84.71
2:V_ALPHA_BF.gw	0.00	1.00	0.32
3:V_GW_DELAY.gw	0.00	500.00	30.50
4:V_GWQMN.gw	0.00	5000.00	2025.00
5:V_GW_REVAP.gw	0.02	0.40	0.35
6:V_REVAPMN.gw	0.00	500.00	122.50
7:V_SOL_AWC(..).sol	0.00	1.00	0.52
8:V_ESCO.bsn	0.00	1.00	0.97
9:V_CH_K2.rte	0.00	500.00	45.50
10:V_CH_N2.rte	0.00	0.30	0.08
11:V_SURLAG.bsn	0.05	24.00	3.14
12:V_RCHRG_DP.gw	0.00	1.00	0.47

Table 4
SWAT calibration & validation.

Type		Period	NSE	R^2
Streamflow	Calibration	1980–1989	0.89	0.9
	Validation	1990–1999	0.84	0.91
	Entire Period	1980–1999	0.86	0.9
Drought Index	SSI 1	1980–1999	0.74	0.76
	SSI 2	1980–1999	0.75	0.77
	SSI 3	1980–1999	0.76	0.77
	SSI 4	1980–1999	0.76	0.78
	SSI 5	1980–1999	0.77	0.78
	SSI 6	1980–1999	0.78	0.79
	SSI 7	1980–1999	0.78	0.80
	SSI 8	1980–1999	0.79	0.80
	SSI 9	1980–1999	0.79	0.80
	SSI 10	1980–1999	0.78	0.80
	SSI 11	1980–1999	0.78	0.79
	SSI 12	1980–1999	0.77	0.79

calibrations (NSE = 0.89 and R^2 = 0.9), validation (NSE = 0.84 and R^2 = 0.91) and entire (NSE = 0.86 and R^2 = 0.9) periods. It can be categorized as a "very good" model based on the Moriasi et al. (2015) performance rating guidelines. However, SWAT seems to be slightly overestimating the base flow in KRB. This might be due to the high evapotranspiration rate in the tropical region. Additionally, using the base flow as freshwater supply could also be one of the reasons contributing to the overestimation. There is no dam or reservoir within the basin, therefore, more attention was paid on the groundwater parameters adjustment.

In general, SWAT was able to reproduce few major historical drought events within the basin, i.e. the 1982, 1987 and 1997–1998 drought events. Moreover, a comparison between SWAT-based SSI and observed SSI was conducted using from one to twelve-month time scales during the period of 1980–1999 (Fig. 4 and Table 4). Interestingly, SWAT showed a "good" performance in simulating SSI for all the evaluated time scales, with the NSE and R^2 values recorded at 0.74–0.79 and 0.76–0.80, respectively. Fig. 4 shows that SWAT managed to capture the SSI variability most of the time, except for the 1989–1990 period. A drought event was detected using from four to twelve-month scales by the observed SSI in 1989–1990, but SWAT-based SSI indicated this period was in a normal condition. This is likely because SWAT overestimated the base flow from 1988 onward (Fig. 3). In this study, SWAT was used for hydrological drought assessment without further modification because SWAT can capture most of the drought events in one- to three-month SSI and Malaysian droughts normally recover within three months.

3.2. CORDEX-SEA bias correction

A comparison of the original and bias-corrected CORDEX-SEA projections with observed historical average monthly precipitation and maximum and minimum temperatures in the KRB can be found in Fig. 5. The monthly precipitation amount was overestimated by the original RCMs as three to five times higher than observations. Additionally, the original RCMs generated a bi-modal precipitation annual cycle, which is consistent with observations, but the primary peak in Nov–Dec was shifted one or two months earlier. This finding is similar to that of Tan et al. (2019b), who evaluated the CORDEX-SEA RCMs' performance in southern Peninsular Malaysia. The quantile mapping method adjusted the mismatch of primary peak and overestimation in precipitation amount.

The maximum and minimum temperatures were well generated by the original RCMs compared to precipitation. Basically, the original RCMs underestimated both the observed maximum and minimum temperatures; the latter had a smaller error. Additionally, a larger variability in historical temperature measurement among RCMs was
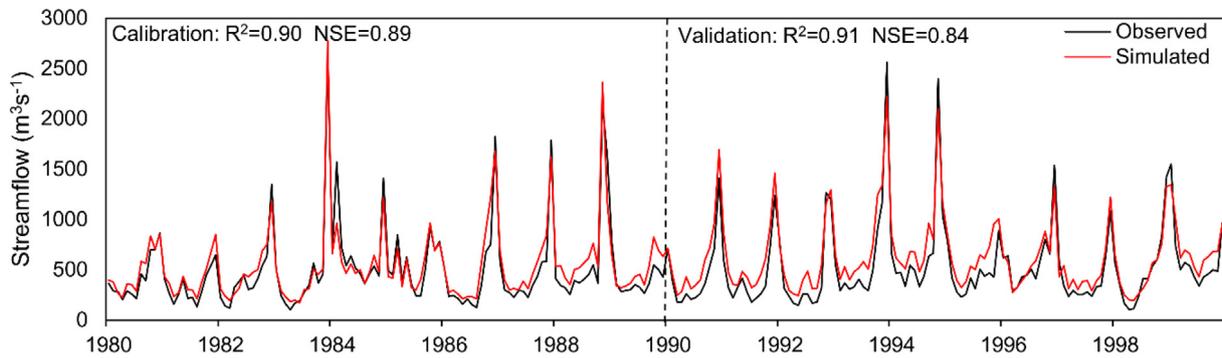
Fig. 3. SWAT monthly streamflow calibration & validation.

found during the southwest monsoon season from June to September. Only REGCM4CSIRO showed a consistent peak maximum temperature with observations in April. By contrast, the peak of maximum temperature for other RCMs was much delayed and normally occurred between June and September. Fig. 5 (e) and (f) indicate that the biases in temperature data were substantially decreased after bias correction using QM.

3.3. Future climatic changes

The annual precipitation over KRB projected by CORDEX-SEA is projected to change from −8.19 to 13.11% and − 13.35 to 10.10%, by the end of the 21st century under the RCP4.5 and RCP8.5 scenarios,

respectively (Fig. 6). It is interesting to note that monthly precipitation during the monsoon flood period (November and December) is projected to change from −62.23 to 38.19% and − 49.95 to 26.92% by the end of 21st century under the RCP4.5 and 8.5 scenarios, respectively (Fig. 7). The climate projections in December is contrary to the study of Tan et al. (2017c), which reported an increase of only up to 60% changes. A possible explanation for this might be due to the difference in GCM downscaling approaches in both studies, where Tan et al. (2017c) used a simpler delta statistical downscaling approach. As mentioned by Zhu et al. (2019), different downscaling approaches have a major impact on the high-flows analysis; therefore, a different sign was found in December. In the two driest months (January and February), most of the RCMs projected a decrease in precipitation amount
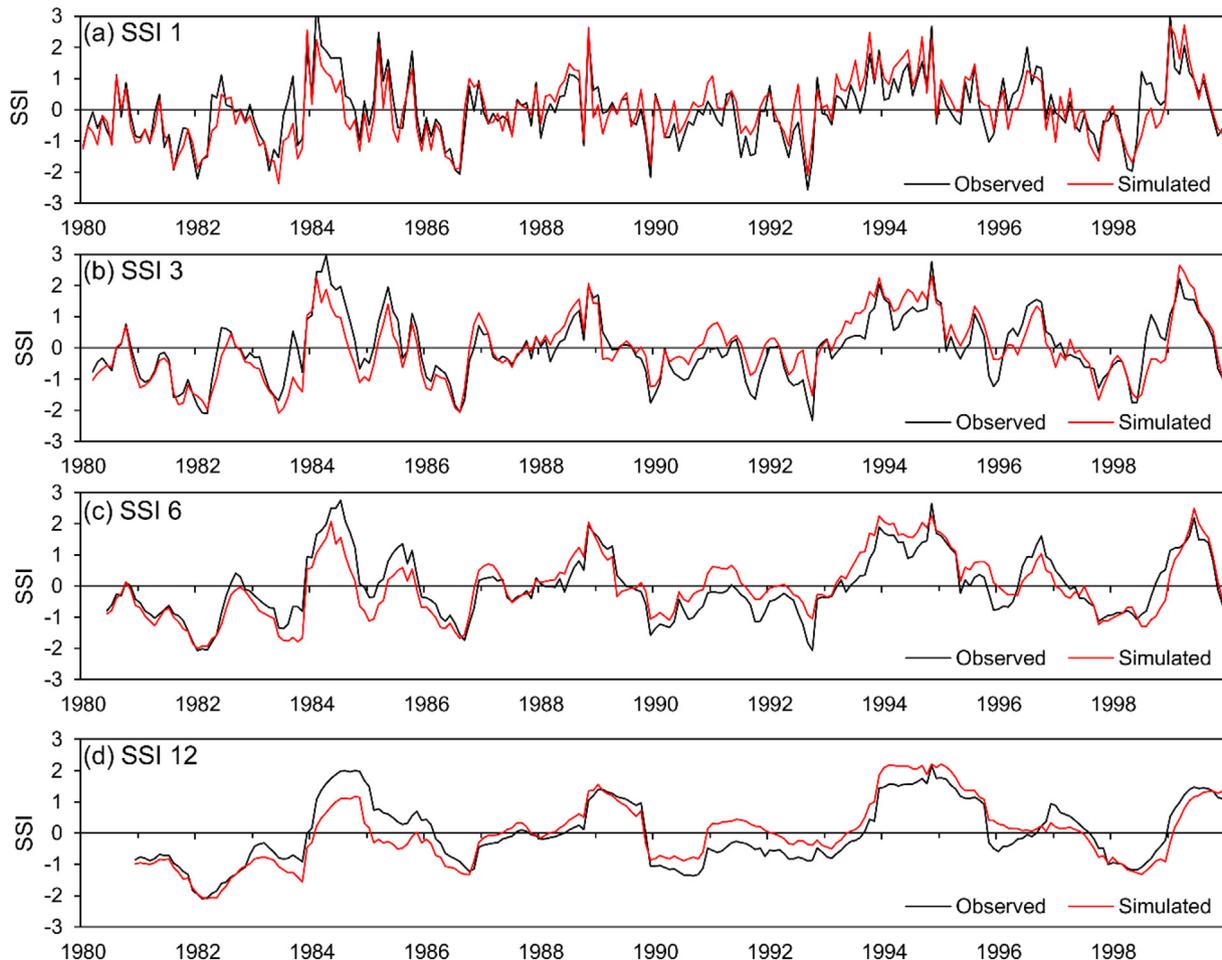

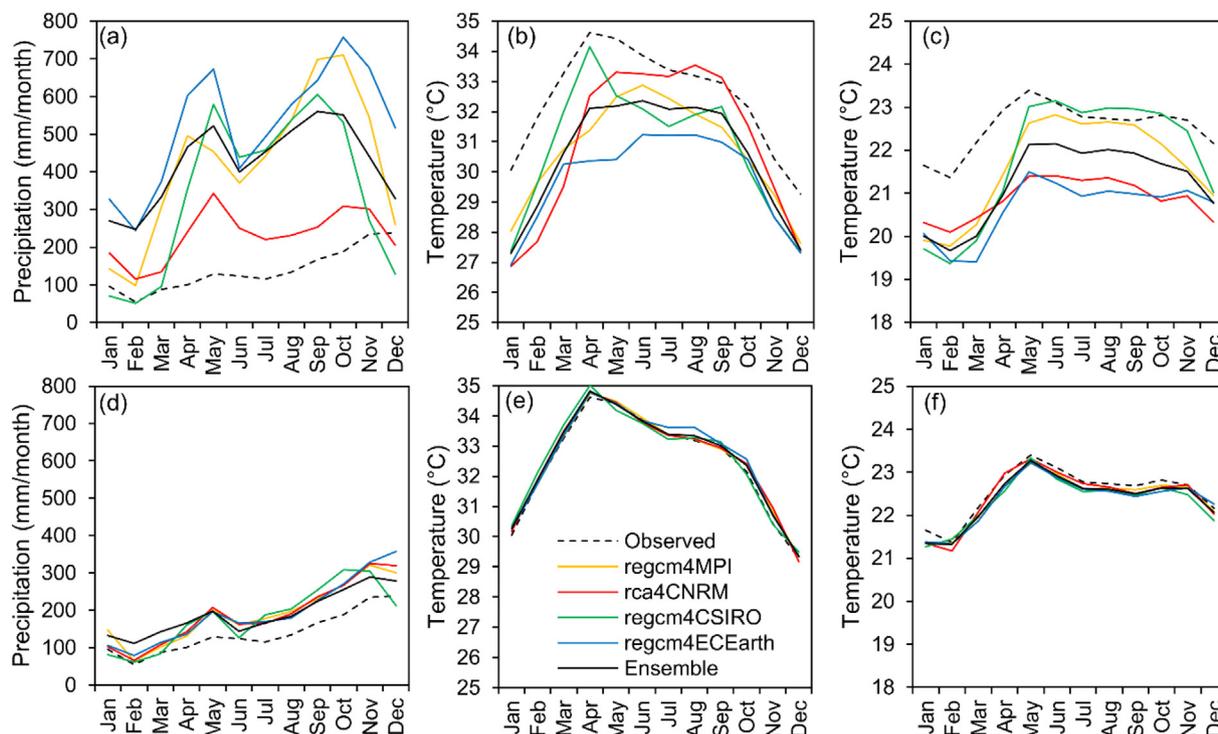**Fig. 4.** SWAT SSI validation for (a) one, (b) three, (c) six and (d) twelve time scales.

Fig. 5. Comparison of the climatology cycle between original (a) precipitation, (b) maximum temperature, (c) minimum temperature and bias corrected (d) precipitation, (e) maximum temperature and (f) minimum temperature.
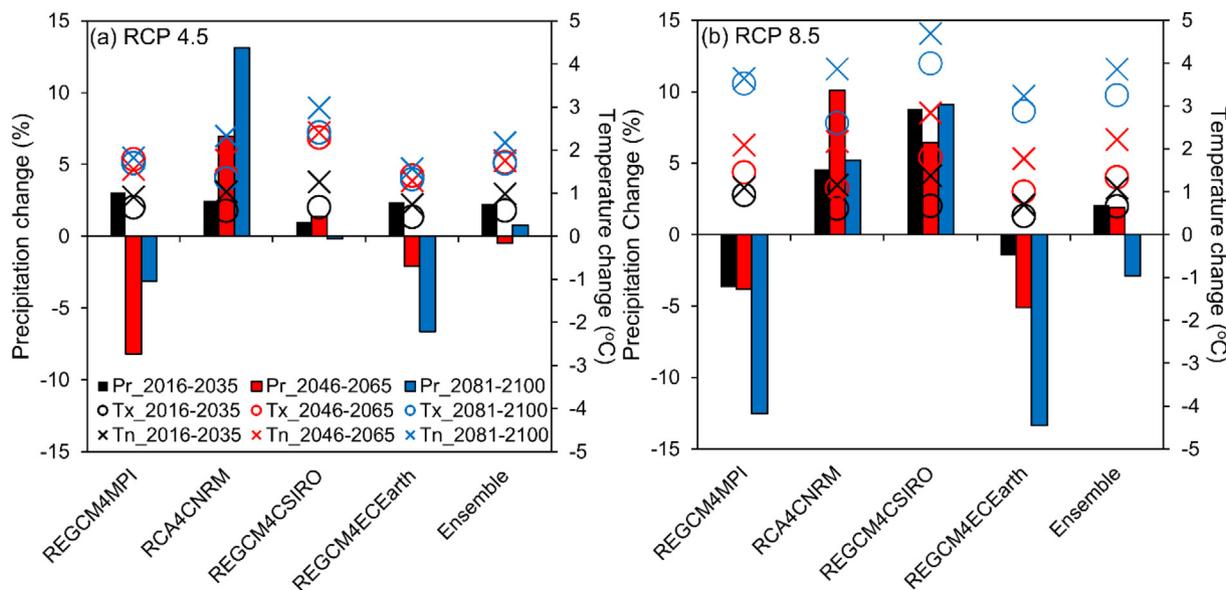

Fig. 6. Future annual precipitation and temperature changes under (a) RCP4.5 and (b) RCP8.5 scenarios.

under both the RCP4.5 and 8.5 scenarios, particularly in the middle and end of the 21st century.

All RCMs projected an increasing trend for both the maximum and minimum temperatures as illustrated in Fig. 6. As compared to the baseline period, the absolute changes of annual maximum temperature were 0.45–0.67 °C, 1.37–2.29 °C and 1.32–2.41 °C under RCP4.5, and 0.43–0.93 °C, 1.00–1.80 °C and 2.61–3.99 °C under RCP8.5, during the 2016–2035, 2046–2065 and 2081–2100 periods, respectively. Similarly, the annual minimum temperature is projected to increase by 0.73–1.26 °C, 1.28–2.41 °C and 1.57–2.98 °C under RCP4.5, and 0.70–1.37 °C, 1.77–2.84 °C and 3.23–4.69 °C under RCP8.5, during the 2016–2035, 2046–2065 and 2081–2100 periods, respectively. The

increasing rate of minimum temperature was higher than the maximum temperature, which is associated with the Songkhram River Basin, Thailand (Shrestha et al., 2018). Similarly, the monthly maximum and minimum temperatures were projected to increase throughout the year, with a higher increasing rate in January, February, March and April (Fig. 7). The highest monthly temperature increases (more than 6 °C) was found in January and February in the 2081–2100 period, as projected by REGCM4CSIRO under RCP8.5. The findings show that a drier condition might occur in January and February due to the lower monthly precipitation amount and higher temperature rate.

Fig. 8 shows the boxplots for the number, intensity and duration of future SPI compared to the baseline period at all the evaluated rainfall
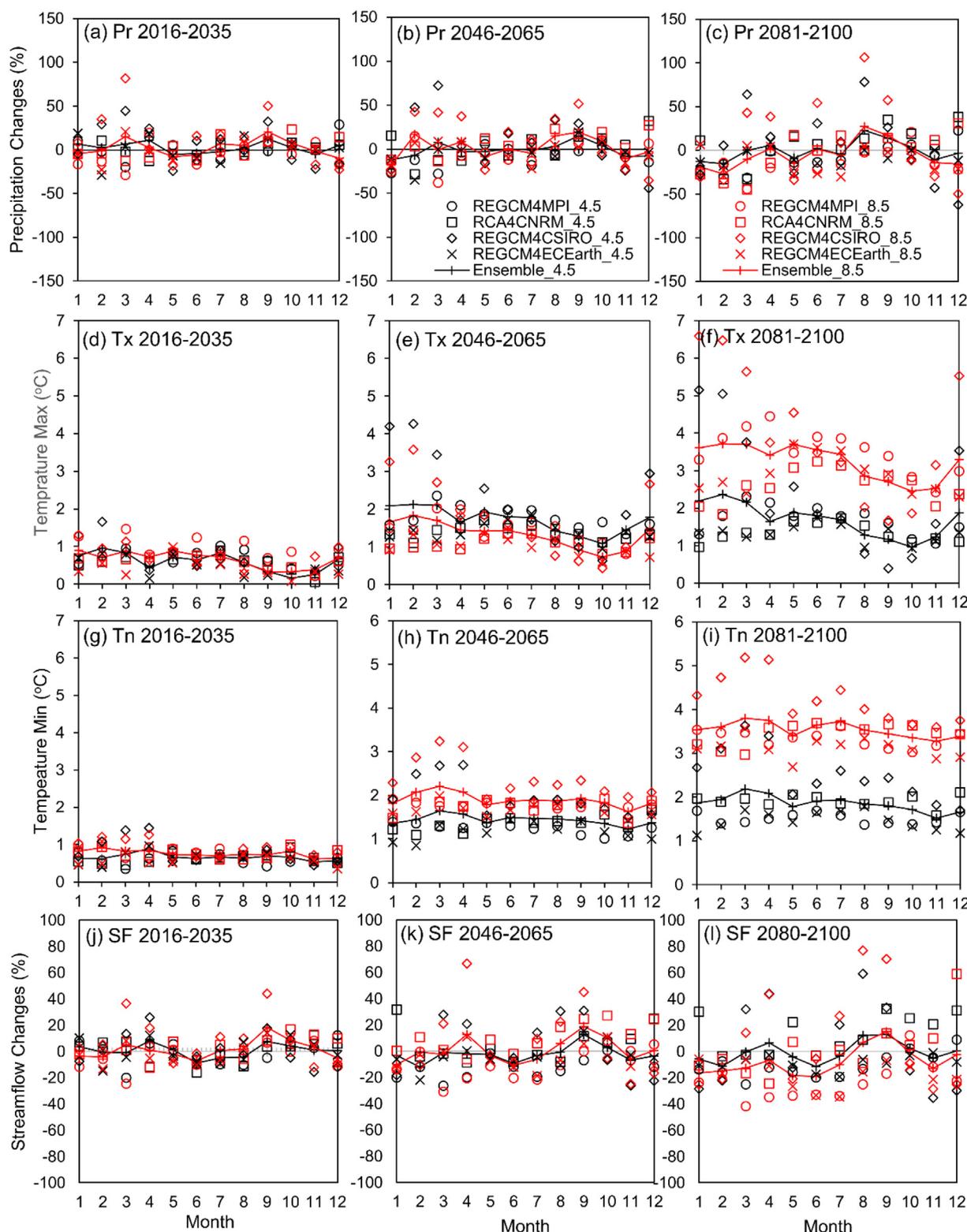
Fig. 7. Future monthly (a, b, c) precipitation, (d, e, f) maximum temperature, (g, h, i), minimum temperature and (j, k, h) streamflow changes over Kelantan River Basin.

stations. REGCM4MPI projected relatively more and longer meteorological drought events than the other three RCMs. The number, intensity and duration of future meteorological droughts were projected to vary from −4 to 4 events, −0.5 (drier) to 0.5 (less dry) and −4 and 4 months by 2100 under both the RCP scenarios. There is a clear sign that meteorological drought duration is expected to become longer in the 2081–2100 period under RCP4.5. Besides that, RCA4CNRM showed that more intense meteorological drought conditions will be found at more than 50% of the rainfall stations in the 2016–2035 period under RCP8.5. Similarly, Supari et al. (2020) reported increases of consecutive dry days in the northeast region of Peninsular Malaysia as simulated by an ensemble of CORDEX-SEA projections, particularly
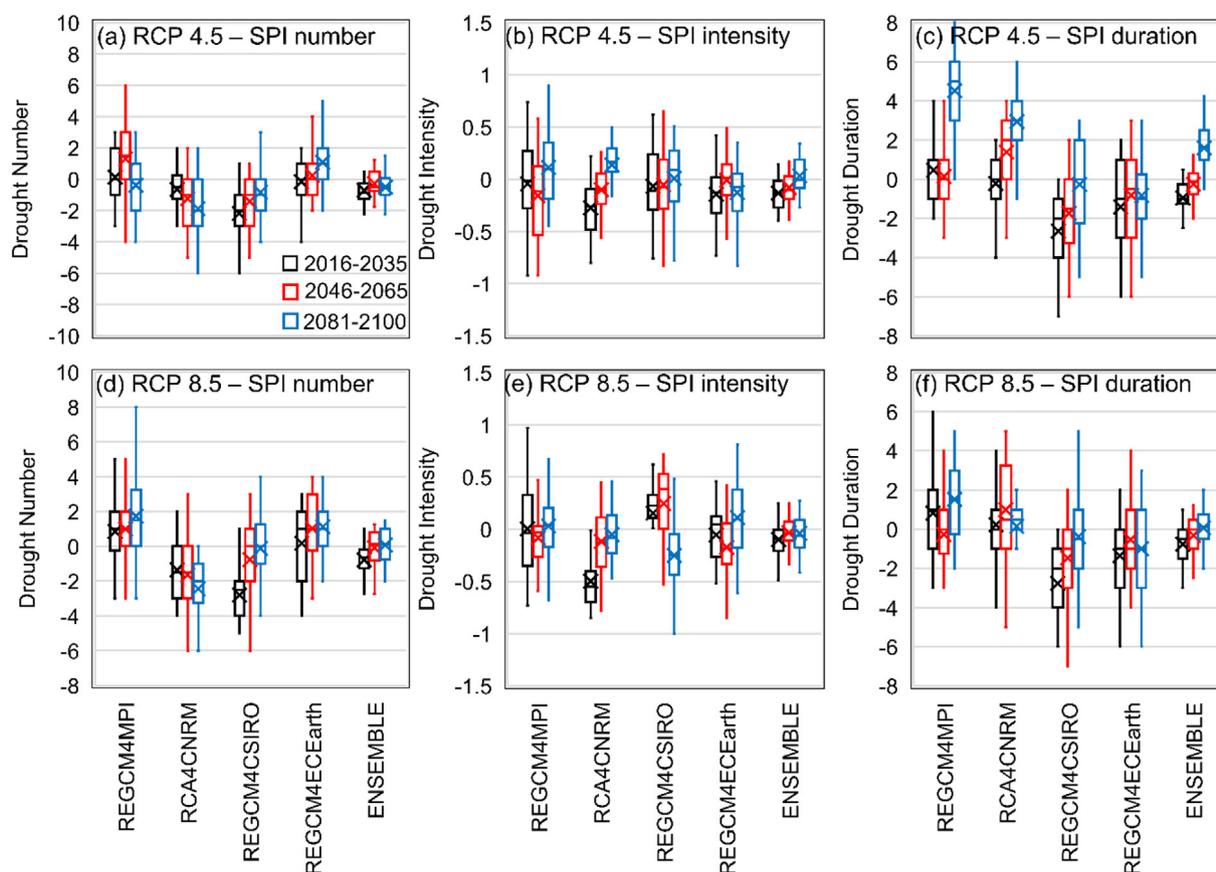
Fig. 8. The number, intensity and duration of SPI under (a, b, c) RCP4.5 and (d, e, f) RCP8.5.

under RCP8.5.

3.4. Future hydrological changes

Annual streamflow is projected to change from −0.33 to 12.16%, −10.73 to 5.72% and − 8.36 to 31.09% during the 2016–2035, 2045–2065 and 2081–2100 periods under RCP4.5, respectively. Meanwhile, annual streamflow is expected to vary from −2.27 to 9.87%, −6.94 to 11.69% and − 19.87 to 13.24% in the 2016–2035, 2045–2065 and 2081–2100 periods under RCP8.5, respectively. The reductions in annual streamflow are more likely to occur in the 2046–2065 period of RCP4.5 and the 2081–2100 period of RCP8.5, covering most of the sub-basins with a drier condition in the north-western region (Fig. 9).

Monthly streamflow in the monsoon flood period (November and December) is projected to change from −15.63 to 12.84%, −26.17 to 24.80% and − 35.32 to 59.04% during the 2016–2035, 2046–2065 and 2081–2100 periods, respectively (Fig. 7). Meanwhile, monthly streamflow in September is projected to increase in all the three future periods for both the RCP scenarios. Most of the RCMs projected a reduction of monthly streamflow in January, February and June, especially in the 2046–2065 and 2081–2100 periods, except RCA4CNRM, (Fig. 5). Similarly, Adnan and Atkinson (2011) also reported a significant decreasing streamflow trend during the dry season between 1975 and 2006 in the downstream region of KRB.

The hydrological drought number, intensity and duration changes at the outlets of all 81 sub-basins are illustrated in Fig. 10. The number of hydrological droughts is projected to vary from −4 to 2 events in most sub-basins under all the studied periods and RCPs. Only RE-GCM4ECEarth projected more hydrological drought events, particularly under RCP8.5. The intensity and duration of hydrological droughts will change from −0.5 (more intense) to 0.5 (less intense) and − 5 to

5 months by the end of the 21st century. Similarly, only REGCM4MPI projected more intense drought events in most of the evaluated periods and RCP scenarios. Under RCP8.5, REGCM4MPI and RCA4CNRM mainly showed an increase in hydrological drought duration, while another two RCMs showed a reduction. Therefore, there is not enough evidence to show that hydrological drought will become more significant in the near future.

3.5. Limitations

Applications of CORDEX-SEA projections are usually focused solely on climate studies including future climate quantification (Tangang et al., 2020; Tangang et al., 2019; Tangang et al., 2018), RCMs performance assessment (Ngo-Duc et al., 2017) and bias correction (Ngai et al., 2020; Ngai et al., 2017). Ideally, it should also be applied to other applications, such as in the domain of human health, landslides, agriculture, biodiversity, ecosystems and businesses in SEA. CORDEX-SEA was first applied in hydrology applications by Tan et al. (2019b) to study future hydro-meteorological droughts in the Johor River Basin (JRB), Malaysia. Incorporation of the downscaled SEA climate projections could produce a more reliable impact assessment. However, narrowing the gap between CORDEX-SEA and other research fields is essential to foster CORDEX-SEA applications. For example, developing the bias corrected CORDEX-SEA projections in SWAT format, readily available on the SWAT website, could increase its usage by the hydrology research community. Besides that, application of more CORDEX-SEA projections is essential to increase the confident level of future hydro-climatic and drought projections.

Good quality observed climate data, characterized by low missing values and well distributed across river basins, is lacking in many regions in Southeast Asia (Tan et al., 2019b). This issue does not only affect the CORDEX-SEA bias correction result but also impedes SWAT
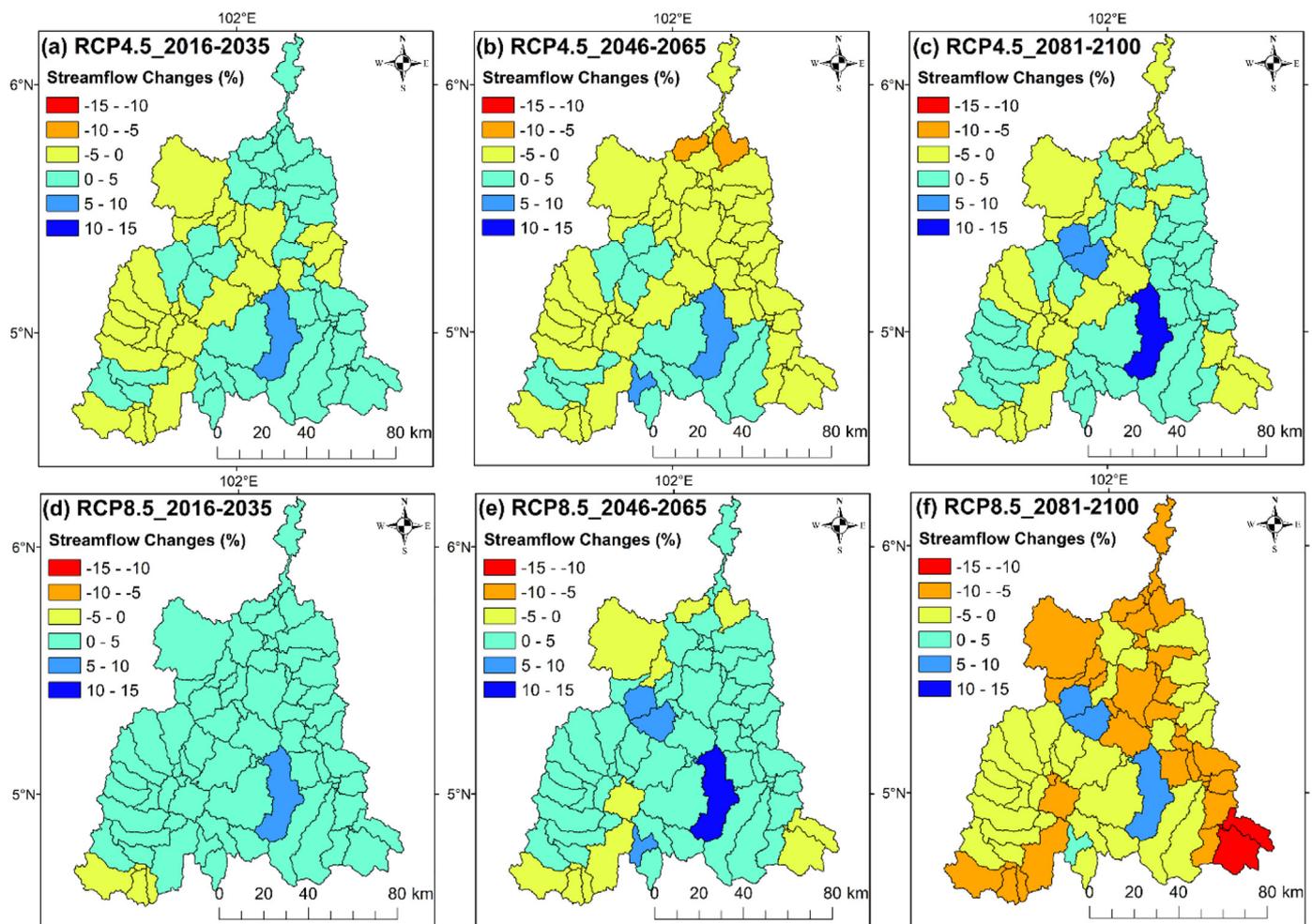
Fig. 9. Annual streamflow changes simulated by ensemble RCMs under (a, b, c) RCP4.5 and (d, e, f) RCP8.5.

development. For example, more than 20% missing values could cause a huge impact on tropical streamflow simulation (Tan and Yang, 2020). Yatagai et al. (2012) constructed a 57-year daily gridded precipitation dataset for Asia based on thousands of Asian stations, called Asian Precipitation – Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) to solve the problem of poor climate observations. Many studies reported that APHR-ODITE is reliable to be used for hydrological modelling in Southeast Asia (Tan et al., 2017a; Thom et al., 2017). Ngai et al. (2017) bias-corrected CORDEX-SEA RCMs using daily precipitation and mean temperature data from APHRODITE, but some popular hydrological models, i.e. SWAT requires daily maximum and minimum temperature data for model setup. Future research should be undertaken to identify and investigate suitable gridded daily maximum and minimum temperature data for bias correcting CORDEX-SEA (Tan et al., 2020).

In general, CMIP5 climate models are mainly applied in droughts assessment studies (Alamgir et al., 2020; Campozano et al., 2020; Qutbudin et al., 2019; Tan et al., 2019b). New CMIP6 models that incorporated the global warming 1.5 °C and 2 °C scenarios just recently available to align with the upcoming 2021 IPCC sixth assessment report (AR6) (Eyring et al., 2016). However, CMIP6 models are available mainly at global and continental scales, where these projections need to be downscaled to finer scales at specific geographical location before applying into any local-scale assessment. Currently in Southeast Asia, there is limited research on downscaling the CMIP6 climate models, and this gap need to be addressed in the near future.

The SWAT calibration and validation process is normally conducted using streamflow, sediment yield and/or water quality outputs (Strauch

and Volk, 2013). In fact, there is limited research on the topic of SWAT calibration and validation using extreme flows or indices (Tan et al., 2020). This study tackled the issue by validating the SSI simulated by SWAT with observed SSI. However, a more comprehensive SWAT extreme calibration and validation scheme is required, i.e. introduction of a third metric. Using only NSE and R^2 statistical metrics seem insufficient to assess extreme events. Additionally, a further study with more focus on developing SWAT-based basin-scale extreme indices is recommended. SWAT can produce various hydrological outputs such as water yield and evapotranspiration, that have the potential to be used to create a new basin-scale drought index.

4. Conclusions

In this study, bias-corrected CORDEX-SEA climate projections were incorporated into the SWAT model to evaluate hydro-meteorological droughts of the Kelantan River Basin, Malaysia. In general, SWAT performed well in monthly streamflow and SSI simulations, and managed to capture most of the historical droughts correctly. Additionally, the quantile mapping method significantly increased the accuracy of RCMs by correcting the mismatch of the amount and peaks in precipitation and maximum and minimum temperatures.

The annual precipitation and maximum and minimum temperatures are projected to change from −8.19 to 13.11% (−13.35 to 10.10%), 0.45 to 2.41 °C (0.43 to 3.99 °C) and 0.73 to 2.98 °C (0.70 to 4.69 °C) by the end of the 21st century, under the RCP4.5 (RCP8.5) scenario, as shown in Fig. 6. This would cause the annual streamflow to vary from −10.37 to 31.09% and − 19.87 to 13.24% under RCP4.5 and 8.5,
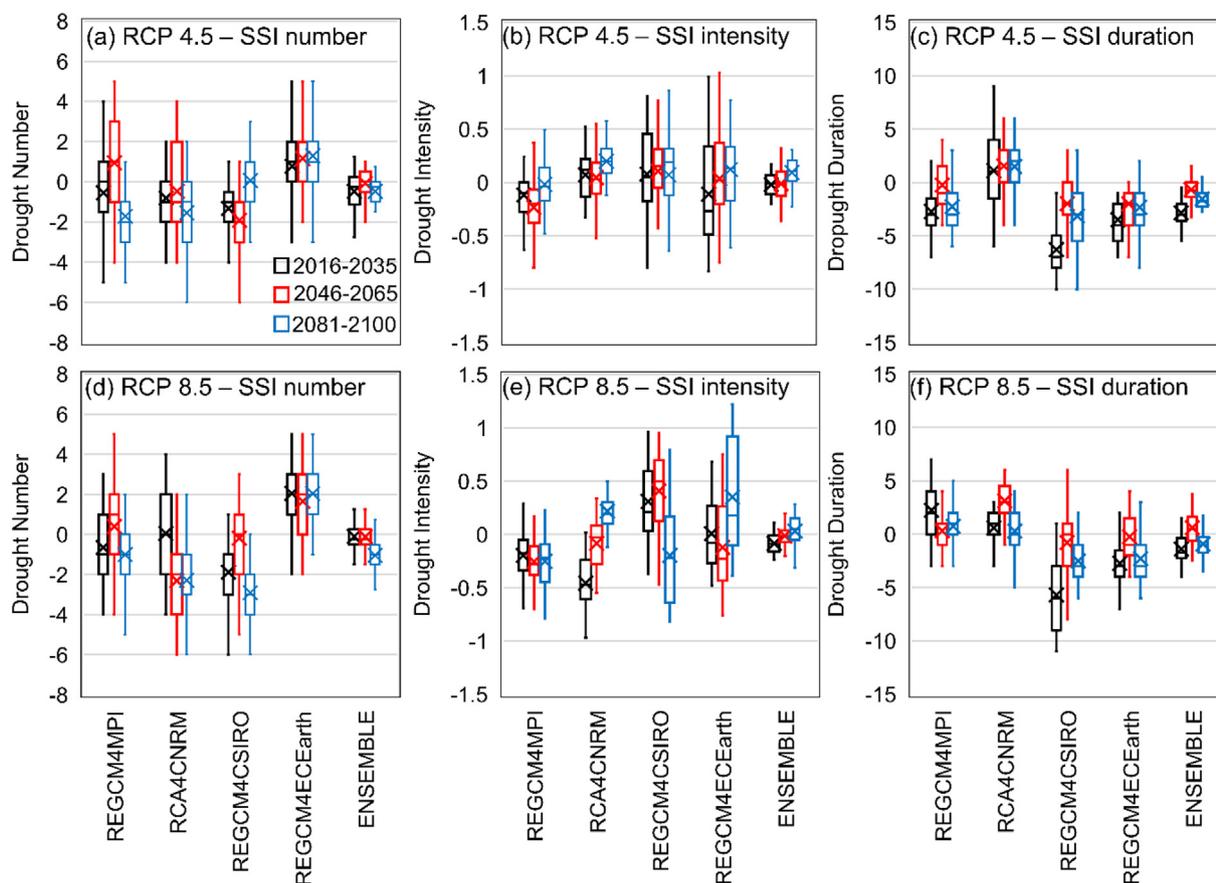
Fig. 10. The number, intensity and duration of SSI under (a, b, c) RCP4.5 and (d, e, f) RCP8.5.

respectively, with the reductions are mainly found in the northwestern region of KRB. Monthly precipitation and streamflow would be likely to decrease in January and February and increase in September. There is a clear sign that meteorological drought duration would most likely become longer under RCP4.5 in 2081–2100. Meanwhile, there is not enough evidence to claim that hydrological drought will become more significant in the near future.

The challenge now is to bias correct CORDEX-SEA for all Southeast Asia, not only for the precipitation data, but also the maximum and minimum temperatures (Tan et al., 2020). The availability of bias-corrected CORDEX-SEA projections at the local scale will allow more multi-discipline studies to be carried out in the near future. Considerably more work will need to be done to determine a suitable third metric instead of NSE and R^2 for assessing SWAT extreme simulations. Lastly, further research should be undertaken to explore the possibility of a SWAT-based drought index development that fully utilizes the SWAT outputs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

References

Abbaspour, K.C., Vejdani, M., Haghighat, S., 2007. SWAT-CUP calibration and uncertainty programs for SWAT. Modsim International Congress on Modelling & Simulation Land Water & Environmental Management Integrated Systems for Sustainability 364 (3), 1603–1609.

ADInet, 2019. The ASEAN Disaster Information Network. https://ahacentre.org/disaster-monitoring/ (accessed on 7 Dec 2019).

Adnan, N.A., Atkinson, P.M., 2011. Exploring the impact of climate and land use changes on streamflow trends in a monsoon catchment. Int. J. Climatol. 31 (6), 815–831.

Alamgir, M., Khan, N., Shahid, S., Yaseen, Z.M., Dewan, A., Hassan, Q., Rasheed, B., 2020. Evaluating severity–area–frequency (SAF) of seasonal droughts in Bangladesh under climate change scenarios. Stoch. Env. Res. Risk A. 34 (2), 447–464.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: Model development. JAWRA Journal of the American Water Resources Association 34 (1), 73–89.

Arnold, J., Moriasi, D., Gassman, P., Abbaspour, C., White, M., Srinivasan, R., Santhi, C., Harmel, R., van Griensven, A., Van Liew, M., Kannan, N., Jha, M., 2012. SWAT: Model use, calibration, and validation. Trans. ASABE 55 (4), 1491–1508.

Bieger, K., Arnold, J.G., Rathjens, H., White, M.J., Bosch, D.D., Allen, P.M., Volk, M., Srinivasan, R., 2017. Introduction to SWAT+, a completely restructured version of the soil and water assessment tool. JAWRA Journal of the American Water Resources Association 53 (1), 115–130.

Bong, C.H.J., Richard, J., 2020. Drought and climate change assessment using Standardized Precipitation Index (SPI) for Sarawak River Basin. Journal of Water and Climate Change. https://doi.org/10.2166/wcc.2019.036. (in press).

Brázdil, R., Mikšovský, J., Štěpánek, P., Zahradníček, P., Řezníčková, L., Dobrovolný, P.,

2019. Forcings and projections of past and future wind speed over the Czech Republic. Clim. Res. 77 (1), 1–21.

Campozano, L., Ballari, D., Montenegro, M., Avilés, A., 2020. Future meteorological droughts in ecuador: decreasing trends and associated spatio-temporal features derived from CMIP5 models. Front. Earth Sci. 8 (17).

Charles, S.P., Chiew, F.H.S., Potter, N.J., Zheng, H., Fu, G., Zhang, L., 2019. Impact of downscaled rainfall biases on projected runoff changes. Hydrol. Earth Syst. Sci. Discuss. 2019, 1–29.

Chi, X., Cubasch, U., Sodoudi, S., 2019. Assessment of human bio-meteorological environment over the Tibetan Plateau region based on CORDEX climate model projections. Theor. Appl. Climatol. 137, 893–907.

Dubey, S.K., Sharma, D., 2018. Assessment of climate change impact on yield of major crops in the Banas River Basin, India. Sci. Total Environ. 635, 10–19.

EM-DAT, 2019. EM-DAT: The Emergency Events Database - Université catholique de Louvain (UCL) - CRED. www.emdat.be Brussels, Belgium.

Eyring, V., Bony, S., Meehl, G.A., Senior, C.A., Stevens, B., Stouffer, R.J., Taylor, K.E., 2016. Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. Geosci. Model Dev. 9 (5), 1937–1958.

Gassman, P.W., Reyes, M.R., Green, C.H., Arnold, J.G., 2007. The soil and water assessment tool: historical development, applications, and Future Research Directions. Trans. ASABE 50 (4), 1211–1250.

Giorgi, F., Jones, C., Asrar, G.R., 2009. Addressing climate information needs at the regional level: the CORDEX framework. World Meteorological Organization (WMO) Bulletin 58 (3), 175.

Juneng, L., Tangang, F., Chung, J.X., Ngai, S.T., Teh, T.W., Narisma, G., Cruz, F., Phan-Van, T., Ngo-Duc, T., Santisirisomboon, J., Singhruck, P., Gunawan, D., Aldrian, E., 2016. Sensitivity of Southeast Asia rainfall simulations to cumulus and air–sea flux parameterizations in RegCM4. Clim. Res. 69 (1).

Khatiwada, K.R., Pandey, V.P., 2019. Characterization of hydro-meteorological drought in Nepal Himalaya: A case of Karnali River Basin. Weather and Climate Extremes 26, 100239.

Knutti, R., Sedláček, J., 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nat. Clim. Chang. 3 (4), 369–373.

Lacressonnière, G., Foret, G., Beekmann, M., Siour, G., Engardt, M., Gauss, M., Watson, L., Andersson, C., Colette, A., Josse, B., Marécal, V., Nyiri, A., Vautard, R., 2016. Impacts of regional climate change on air quality projections and associated uncertainties. Clim. Chang. 136 (2), 309–324.

Lee, M.H., Im, E.S., Bae, D.H., 2019. Impact of the spatial variability of daily precipitation on hydrological projections: a comparison of GCM- and RCM-driven cases in the Han River basin, Korea. Hydrol. Process. 33 (16), 2240–2257.

Marchane, A., Tramblay, Y., Hanich, L., Ruelland, D., Jarlan, L., 2017. Climate change impacts on surface water resources in the Rheraya catchment (High Atlas, Morocco). Hydrol. Sci. J. 62 (6), 979–995.

McKee, T.B., 1993. The Relationship of Drought Frequency and Duration of Time Scales. Eighth Conference on Applied Climatology, January, Anaheim, California 1993, 17–22.

Mishra, A.K., Singh, V.P., 2011. Drought modeling – A review. J. Hydrol. 403 (1), 157–175.

Moriasi, D.N., Gitau, M.W., Pai, N., Daggupati, P., 2015. Hydrologic and water quality models: performance measures and evaluation criteria. Trans. ASABE 58 (6), 1763–1785.

Ngai, S.T., Tangang, F., Juneng, L., 2017. Bias correction of global and regional simulated daily precipitation and surface mean temperature over Southeast Asia using quantile mapping method. Glob. Planet. Chang. 149, 79–90.

Ngai, S.T., Juneng, L., Tangang, F., Chung, J.X., Salimun, E., Tan, M.L., Amalia, S., 2020. Future projections of Malaysia daily precipitation characteristics using bias correction technique. Atmos. Res. 104926.

Ngo-Duc, T., Tangang, F.T., Santisirisomboon, J., Cruz, F., Trinh-Tuan, L., Nguyen-Xuan, T., Phan-Van, T., Juneng, L., Narisma, G., Singhruck, P., Gunawan, D., Aldrian, E., 2017. Performance evaluation of RegCM4 in simulating extreme rainfall and temperature indices over the CORDEX-Southeast Asia region. Int. J. Climatol. 37 (3), 1634–1647.

Oguntunde, P.G., Abiodun, B.J., Lischeid, G., 2017. Impacts of climate change on hydro-meteorological drought over the Volta Basin, West Africa. Glob. Planet. Chang. 155, 121–132.

Qutbudin, I., Shiru, M.S., Sharafati, A., Ahmed, K., Al-Ansari, N., Yaseen, Z.M., Shahid, S., Wang, X., 2019. Seasonal drought pattern changes due to climate variability: case study in Afghanistan. Water 11 (5), 1096.

Roy, T., Valdés, J.B., Lyon, B., Demaria, E.M.C., Serrat-Capdevila, A., Gupta, H.V., Valdés-Pineda, R., Durcik, M., 2018. Assessing hydrological impacts of short-term climate change in the Mara River basin of East Africa. J. Hydrol. 566, 818–829.

Rummukainen, M., 2016. Added value in regional climate modeling. WIREs Climate Change 7 (1), 145–159.

Sam, T.T., Khoi, D.N., Thao, N.T.T., Nhi, P.T.T., Quan, N.T., Hoan, N.X., Nguyen, V.T., 2019. Impact of climate change on meteorological, hydrological and agricultural droughts in the Lower Mekong River Basin: a case study of the Srepok Basin, Vietnam. Water and Environment Journal 33 (4), 547–559.

Shrestha, M., Acharya, S.C., Shrestha, P.K., 2017. Bias correction of climate models for hydrological modelling – are simple methods still useful? Meteorol. Appl. 24 (3), 531–539.

Shrestha, S., Bhatta, B., Shrestha, M., Shrestha, P.K., 2018. Integrated assessment of the climate and landuse change impact on hydrology and water quality in the Songkhram River Basin, Thailand. Sci. Total Environ. 643, 1610–1622.

Singh, V., Jain, S.K., Singh, P.K., 2019. Inter-comparisons and applicability of CMIP5 GCMs, RCMs and statistically downscaled NEX-GDDP based precipitation in India. Sci. Total Environ. 697, 134163.

Strauch, M., Volk, M., 2013. SWAT plant growth modification for improved modeling of perennial vegetation in the tropics. Ecol. Model. 269, 98–112.

Supari, Tangang, Juneng, L., Cruz, F., Chung, J.X., Ngai, S.T., Salimun, E., Mohd, M.S.F., Santisirisomboon, J., Singhruck, P., PhanVan, T., Ngo-Duc, T., Narisma, G., Aldrian, E., Gunawan, D., Sopaheluwakan, A., 2020. Multi-model projections of precipitation extremes in Southeast Asia based on CORDEX-Southeast Asia simulations. Environ. Res. 184, 109350.

Tan, M.L., Yang, X., 2020. Effect of rainfall station density, distribution and missing values on SWAT outputs in tropical region. J. Hydrol. 584 (2020), 124660.

Tan, M.L., Gassman, P.W., Cracknell, A.P., 2017a. Assessment of three long-term gridded climate products for hydro-climatic simulations in tropical river basins. Water 9 (3), 229.

Tan, M.L., Ibrahim, A.L., Cracknell, A.P., Yusop, Z., 2017b. Changes in precipitation extremes over the Kelantan River Basin, Malaysia. Int. J. Climatol. 37 (10), 3780–3797.

Tan, M.L., Ibrahim, A.L., Yusop, Z., Chua, V.P., Chan, N.W., 2017c. Climate change impacts under CMIP5 RCP scenarios on water resources of the Kelantan River Basin, Malaysia. Atmos. Res. 189, 1–10.

Tan, M.L., Ramli, H.P., Tam, T.H., 2018a. Effect of DEM resolution, source, resampling technique and area threshold on SWAT outputs. Water Resour. Manag. 32 (14), 4591–4606.

Tan, M.L., Samat, N., Chan, N.W., Roy, R., 2018b. Hydro-meteorological assessment of three GPM satellite precipitation products in the Kelantan River Basin, Malaysia. Remote Sens. 10 (7), 1011.

Tan, M.L., Gassman, P.W., Srinivasan, R., Arnold, J.G., Yang, X., 2019a. A Review of SWAT Studies in Southeast Asia: applications, challenges and Future Directions. Water 11 (5), 914.

Tan, M.L., Juneng, L., Tangang, F.T., Chan, N.W., Ngai, S.T., 2019b. Future hydro-meteorological drought of the Johor River Basin, Malaysia, based on CORDEX-SEA projections. Hydrol. Sci. J. 64 (8), 921–933.

Tan, M.L., Gassman, P., Yang, X., Haywood, J., 2020. A Review of SWAT applications. Performance and Future Needs for Simulation of Hydro-Climatic Extremes. Advances in Water Resources 103662.

Tangang, F., Juneng, L., Salimun, E., Sei, K., Loh, J., 2012. Climate Change and Variability over Malaysia: Gaps in Science and Research Information. Sains Malaysiana 41, 1355–1366.

Tangang, F., Supari, S., Chung, J.X., Cruz, F., Salimun, E., Ngai, S.T., Liew, J., Jerasorn, S., Jaruthat, S., Thanh, N.-D., Tan, P.-V., Gemma, N., Patama, S., Dodo, G., Edvin, A., Ardhasena, S., Grigory, N., Hongwei, Y., Armelle, Reca C., Dmitry, S., David, H.-G., 2018. Future changes in annual precipitation extremes over Southeast Asia under global warming of 2°C. APN Science Bulletin 8 (1).

Tangang, F., Santisirisomboon, J., Juneng, L., Salimun, E., Chung, J., Supari, S., Cruz, F., Ngai, S.T., Ngo-Duc, T., Singhruck, P., Narisma, G., Santisirisomboon, J., Wongsaree, W., Promjirapawat, K., Sukamongkol, Y., Srisawadwong, J., Setsirichok, D., Phan-Van, T., Aldrian, E., Gunawan, D., Nikulin, G., Yang, H., 2019. Projected future changes in mean precipitation over Thailand based on multi-model regional climate simulations of CORDEX Southeast Asia. Int. J. Climatol. 39 (14), 5413–5436.

Tangang, F., Chung, J.X., Juneng, L., Supari, Salimun, Ngai, S.T., Jamaluddin, A.F., Mohd, M.S.F., Cruz, F., Narisma, G., Santisirisomboon, J., Ngo-Duc, T., Van Tan, P., Singhruck, P., Gunawan, D., Aldrian, E., Sopaheluwakan, A., Grigory, N., Remedio, A.R.C., Sein, D.V., Hein-Griggs, D., McGregor, J.L., Yang, H., Sasaki, H., Kumar, P., 2020. Projected future changes in rainfall in Southeast Asia based on CORDEX–SEA multi-model simulations. Clim. Dyn. 55, 1247–1267.

Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. Bull. Am. Meteorol. Soc. 93 (4), 485–498.

Thilakarathne, M., Sridhar, V., 2017. Characterization of future drought conditions in the lower Mekong River Basin. Weather and Climate Extremes 17, 47–58.

Thom, V.T., Khoi, D.N., Linh, D.Q., 2017. Using gridded rainfall products in simulating streamflow in a tropical catchment – A case study of the Srepok River Catchment. Vietnam. 65 (1), 18.

UN, 2019. Population Division. World Population Prospects 2019, Volume I: Comprehensive Tables (ST/ESA/SER.A/426). United Nations Department of Economic and Social Affairs.

UN and ASEAN, 2019. Ready for the Dry Years: Building Resilience to Drought in South-East Asia, United Nations Economic and Social Commission for Asia and the Pacific.

Vu, M.T., Raghavan, V.S., Liong, S.-Y., 2015. Ensemble climate projection for hydro-meteorological drought over a river basin in Central Highland, Vietnam. KSCE J. Civ. Eng. 19 (2), 427–433.

Vu, M.T., Vo, N.D., Gourbesville, P., Raghavan, S.V., Liong, S.Y., 2017. Hydro-meteorological drought assessment under climate change impact over the Vu Gia–Thu Bon river basin, Vietnam. Hydrol. Sci. J. 62 (10), 1654–1668.

Wichitarapongsakun, P., Sarin, C., Klomjek, P., Chuenchooklin, S., 2016. Rainfall prediction and meteorological drought analysis in the Sakae Krang River basin of Thailand. Agriculture and Natural Resources 50 (6), 490–498.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N., Kitoh, A., 2012. APHRODITE: constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain Gauges. Bull. Am. Meteorol. Soc. 93 (9), 1401–1415.

Zhu, X., Zhang, A., Wu, P., Qi, W., Fu, G., Yue, G., Liu, X., 2019. Uncertainty impacts of climate change and downscaling methods on future runoff projections in the Biliu River Basin. Water 11 (10), 2130.