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LETTER

Risks of precipitation extremes over Southeast Asia: does 1.5 °C or 2 °C global warming make a difference?

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Abstract

Guided by the target of the Paris Agreement of 2015, it is fundamental to identify regional climate responses to global warming of different magnitudes for Southeast Asia (SEA), a tropical region where human society is particularly vulnerable to climate change. Projected changes in indices characterizing precipitation extremes of the 1.5 °C and 2 °C global warming levels (GWLs) exceeding pre-industrial conditions are analyzed, comparing the reference period (1976–2005) with an ensemble of CORDEX simulations. The results show that projected changes in precipitation extreme indices are significantly amplified over the Indochina Peninsula and the Maritime Continent at both GWLs. The increases of precipitation extremes are essentially affected by enhanced convective precipitation. The number of wet and extremely wet days is increasing more abruptly than both the total and daily average precipitation of all wet days, emphasizing the critical risks linked with extreme precipitation. Additionally, significant changes can also be observed between the GWLs of 1.5 °C and 2 °C, especially over the Maritime Continent, suggesting the high sensitivity of precipitation extremes to the additional 0.5 °C GWL increase. The present study reveals the potential influence of both 1.5 °C and 2 °C GWLs on regional precipitation over SEA, highlights the importance of restricting mean global warming to 1.5 °C above pre-industrial conditions and provides essential information on manageable climate adaptation and mitigation strategies for the developing countries in SEA.

1. Introduction

In December 2015, the 21st Conference of Parties (COP21) of the United Nations Framework Convention of Climate Change (UNFCCC) adopted the Paris Agreement, with the focus on holding the increase in the global average temperature to well below 2 °C, and additionally achieved a more ambitious target to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels (UNFCCC 2015). This agreement aims to significantly reduce the risks and impacts of climate change due to the intense anthropogenic greenhouse gas (GHG) emissions since the 1980s. Given this impetus at a global scale, the Intergovernmental Panel on Climate Change (IPCC) was invited to provide a special report in 2018 on the impacts of global warming at 1.5 °C versus 2 °C, or more focused research on the effects of an additional 0.5 °C warming. Consequently, plenty of analyses on these issues have been conducted to assess the influence of climate on natural and human systems, especially in less-developed countries (Hulme 2016,

Table 1. Summary of the climate model projections used in this study.

RCM		GCM			
Model	Institution	Model	Institution	Model domain	Scenarios (RCP)
RegCM4-3	ICTP, Italy	EC-EARTH	ICHEC, Netherlands/Ireland	SEA	4.5, 8.5
RCA4	SMHI, Sweden	HadGEM2-ES	MOHC, UK	SEA	4.5, 8.5
RegCM4-3	ICTP, Italy	IPSL-CM5A-LR	IPSL, France	SEA	4.5, 8.5
RegCM4-3	ICTP, Italy	MPI-ESM-MR	MPI-M, Germany	SEA	4.5, 8.5
HIRHAM5	DMI, Denmark	EC-EARTH	ICHEC, Netherlands/Ireland	EAS	4.5, 8.5
HadGEM3-RA	MOHC, UK	HadGE[1]M2-AO	MOHC, UK	EAS	4.5, 8.5

[1] ICTP: International Centre for Theoretical Physics; SMHI: Swedish Meteorological and Hydrological Institute; DMI: Danish Meteorological Institute; MOHC: Met Office Hadley Centre; IPSL: Institute Pierre Simon Laplace; ICHEC: Irish Centre for High-End Computing; MPI-M: Max Planck Institute for Meteorology.

Marotzke *et al* 2017, Mba *et al* 2018, Tebaldi and Wehner 2018). These, and many other studies on future climate projections, indicate that the frequency and intensity of climate extremes would inevitably increase in different global warming levels (GWLs) over different regions (Vautard *et al* 2014, Mitchell *et al* 2016, James *et al* 2017). A comprehensive understanding of these climate-sensitive thresholds at regional scales are of primary importance to avoid the potential risks of climate change and to provide recommendations for country-level policymakers (Knutti *et al* 2013, Schleussner *et al* 2016, Chevuturi *et al* 2018, Holden *et al* 2018).

In tropical regions, extreme precipitation events are likely to occur more frequently under rapid global warming (Allen and Ingram 2002). Southeast Asia (SEA) is generally considered to a region that is highly vulnerable to the impact of climate change due to its geographical location and complex topography. Many previous studies have emphasized that tropical warming will proportionally increase atmospheric water vapor content, which is expected to induce enhanced precipitation over the wet regions (Held and Soden 2006, Vecchi *et al* 2006). The IPCC Fifth Assessment Report (AR5) has confirmed that the SEA has already been experiencing significant climate warming. The consequent negative impacts, such as the frequency of high temperature and precipitation extremes, have unequivocally increased over this region (IPCC 2013). The increasing weather and climate extremes may enhance the already high drought and flood risks of developing countries over SEA in the future (IPCC 2014). Therefore, to investigate the impacts on precipitation extremes of 1.5 °C and 2 °C GWLs is a primary task for this region. In addition, it is also important to quantify how the precipitation would change at the 1.5 °C and 2 °C GWLs and whether there is a significant difference in regional climate risks between the two GWLs.

Over the past two decades, climate models have been recognized as effective tools for investigating the historical, present and even future climate (Giorgi *et al* 2009, Moss *et al* 2010, Giorgi *et al* 2012 Cabos *et al* 2017). However, in order to assess the regional impacts of different GWLs there is an increasing demand for high-resolution regional climate information. Regional climate models (RCMs) with advanced parameterizations and dynamically downscaled climate information have been increasingly applied to investigate the response of regional climate to different GWLs (Schleussner *et al* 2017, Lennard *et al* 2018, Maúre *et al* 2018, Nikulin *et al* 2018). With the aim of producing intelligent regional climate projections, the ongoing Coordinated Regional Downscaling Experiment (CORDEX; Giorgi *et al* 2009) is a global collaborative initiative framework under the World Climate Research Programme (WCRP). Recently, ensembles of high-resolution regional climate projections derived from CORDEX models have been widely used to provide the future climate changes of specific regions and to contribute detailed information for climate adaptation and mitigation policies. However, to the best of our knowledge, there is still information missing on the changes of precipitation extremes for different GWLs over SEA. This paper aims to apply the RCM simulations within the CORDEX framework to examine the future changes in precipitation extremes under the 1.5 °C and 2 °C GWLs.

The paper is organized as follows. Model projections and observations and the analysis methods are briefly described in section 2. In section 3 we present the assessment of CORDEX RCM performance and the projected changes in precipitation extremes at different GWLs over SEA. In addition, quantitative findings of precipitation extremes focusing on the additional 0.5 °C warming are provided. Finally, a conclusion and discussion follow in section 4.

2. Data and methods

2.1. Climate data and index representation of extremes

The currently available CORDEX SEA ensemble consists four RCMs (table 1) with a resolution of 25 km. As SEA is also included in the CORDEX East Asia (EAS) runs, two CORDEX EAS models (table 1) are also employed. Additionally, the continental-scale daily gridded precipitation data from the Asian Precipitation —Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE; Yatagai *et al* 2012) project is employed to evaluate the historical simulation of the RCMs used in this study; this contains a dense network of daily rain-gauge data for the whole of Asia and has been confirmed as one of the highest-quality precipitation products (Qi *et al* 2016).

Following the Expert Team on Climate Change Detection and Indices (ETModel domainCCDI; Zhang *et al* 2011), several indices are employed to quantify the precipitation extremes, as displayed in table 2. These are Rx5day (maximum consecutive 5-day precipitation), SDII (simple daily intensity), R10mm/R20mm (heavy/very heavy precipitation days), CDD/CWD (consecutive dry/wet days), PRCPTOT (total precipitation of wet days), R95pTOT/R99pTOT (precipitation of very/extremely wet days). Further information is available in detail at the ETCCDI website http://etccdi.pacificclimate.org/indices.shtml. However, some studies have reported that the fixed climatological percentile indices (R95pTOT and R99pTOT) may have some uncertainties due to outliers, especially at seasonal scales (Zolina *et al* 2009, 2010, Leander *et al* 2014). Alternatively, two new indices are proposed to improve the accuracy of heavy precipitation estimates, such as R95tt and S95pTOT. The R95tt index is estimated by the fractional contribution of R95pTOT to total precipitation based on the gamma probability density function (Zolina *et al* 2009). The S95pTOT assumes a separate 95th percentile for each year based on a Weibull distribution, which fits to the amounts of wet-day precipitation (Leander *et al* 2014). Alexander *et al* (2006) have demonstrated that the R95pTOT and R99pTOT indices are still superior, representing more robust statistical characteristics of precipitation extremes with respect to the distribution tails. Lately, it has been reported that the stability and accuracy of R95tt is qualitatively consistent with R95pTOT, which is for both relatively higher compared with S95pTOT in trend analysis of daily precipitation on an annual scale (Irannezhad *et al* 2017). Hence, the well-established ETCCDI indices (Karl *et al* 1999, WMO workshop) are reasonable in terms of detecting climate change (IPCC 2013, Leander *et al* 2014). Therefore, and particularly for our focus on the annual scale, we apply R95pTOT and R99pTOT as well as the other seven precipitation indices from ETCCDI recommended by the World Meteorological Organization (WMO).

2.2. Definition of the 1.5 °C and 2 °C GWLs

Previous studies (King *et al* 2017, Dosio and Fischer 2018) have demonstrated that little difference in temperature or precipitation patterns over most of the world can be found at a specific GWL under various scenarios of different representative concentration pathways (RCPs); that is, the results of different GWLs are fairly independent of the scenarios. For the RCM downscaling processes, the GWLs depend on their corresponding driving global climate models (GCMs). The period of 1881–1910, available through most CMIP5 historical simulations, is taken as pre-industrial. The time series of the spatially weighted averages of annual global surface air temperature from GCMs are first smoothed by a 30-year running mean to eliminate interannual variability. In order to identify a relatively stable climate mode, the 30-year periods of the running means, which reach 1.5 °C and 2 °C higher than the pre-industrial global mean temperature, are defined as the corresponding GWL crossing times under the RCP scenarios. Accordingly, aiming at future climate change, there are six RCMs all assuming RCP 4.5 and 8.5, respectively, which compose 12 ensemble members in total for each GWL. Hereafter a specific model run is represented by the RCM followed by its corresponding driving GCM in the parentheses, e.g. RegCM4 (EC-EARTH) refers to the regional RegCM4 model driven by the global EC-EARTH model.

2.3. Model performance metrics

In the study, the relative model error is employed to evaluate the climate simulation capability of each individual RCM with regard to various climate parameters, which is represented by the relative root mean squared error (RMSE′; Gleckler *et al* 2008, Dong *et al* 2015) defined as follows. First, the root mean squared error (RMSE) is calculated for each model index with respect to the APHRODITE 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 obtain the RMSE′ of each model via the formula:

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

where $\mathrm{RMSE}_{\mathrm{Median}}$ is the ensemble median RMSE of the existing models. Generally, a negative (positive) RMSE′ indicates a better (worse) performance than half (50%) of the models.

As for the credibility of the projection ensemble results, the signal to noise ratio (SNR) is defined as follows (Shi *et al* 2018):

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

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 the noise, indicating relatively reliable projections. In this study, all statistical significances are performed for the 95% confidence level by employing the two-tailed Student's *t*-test. The warming consequences are presented as the climate differences between the GWLs and the historical 30-year reference period of 1976–2005.

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

Label	Description	Index Definition	Units
Rx5day	Maximum consecutive 5-day precipitation	Let PR_{kj} be the precipitation amount for the 5-day interval ending *k*, period *j*. Then maximum 5-day values for period *j* are: $Rx5day_j = \max(PR_{kj})$	mm
SDII	Simple daily intensity	Let PR_{wj} be the daily precipitation amount on wet days, $PR \geqslant 1$ mm in period *j*. If *W* represents number of wet days in *j*, then: $SDII_j = (\sum_{w=1}^{W} PR_{wj}/W)$	mm
R10mm/R20mm	Heavy/very heavy precipitation days	Let PR_{ij} be the precipitation amount on day *i* in period *j*. Count the number of days where $PR_{ij} > 10$ mm /20 mm	days
CDD/CWD	Consecutive dry/wet days	Let PR_{ij} be the precipitation amount on day *i* in period *j*. Count the largest number of consecutive days where $PR_{ij} < 1$ mm/$PR_{ij} \geqslant 1$, for the dry/wet days	days
PRCPTOT	Total precipitation of wet days	Let PR_{ij} be the daily precipitation amount on day *i* in period *j*. If *I* represents the number of days in *j*, then: $PRCPTOT_j = \sum_{n=1}^{I} PR_{ij}$	mm
R95pTOT	Very wet days precipitation	Let PR_{wj} be the daily precipitation amount on a wet day *w* ($PR \geqslant 1$ mm) in period *i* and let $PR_{wn}95$ be the 95th percentile of precipitation on wet days in the period 1961–1990. If *W* represents the number of wet days in the period, then: $R95_{pj} = \sum_{w=1}^{W} PR_{wj}$, where $PR_{wj} > PR_{wn}95$	mm
R99pTOT	Extremely wet days precipitation	Let PR_{wj} be the daily precipitation amount on a wet day *w* ($PR \geqslant 1$ mm) in period *i* and let $PR_{wn}99$ be the 99th percentile of precipitation on wet days in the period 1961–1990. If *W* represents the number of wet days in the period, then: $R99_{pj} = \sum_{w=1}^{W} PR_{wj}$, where $PR_{wj} > PR_{wn}99$	mm

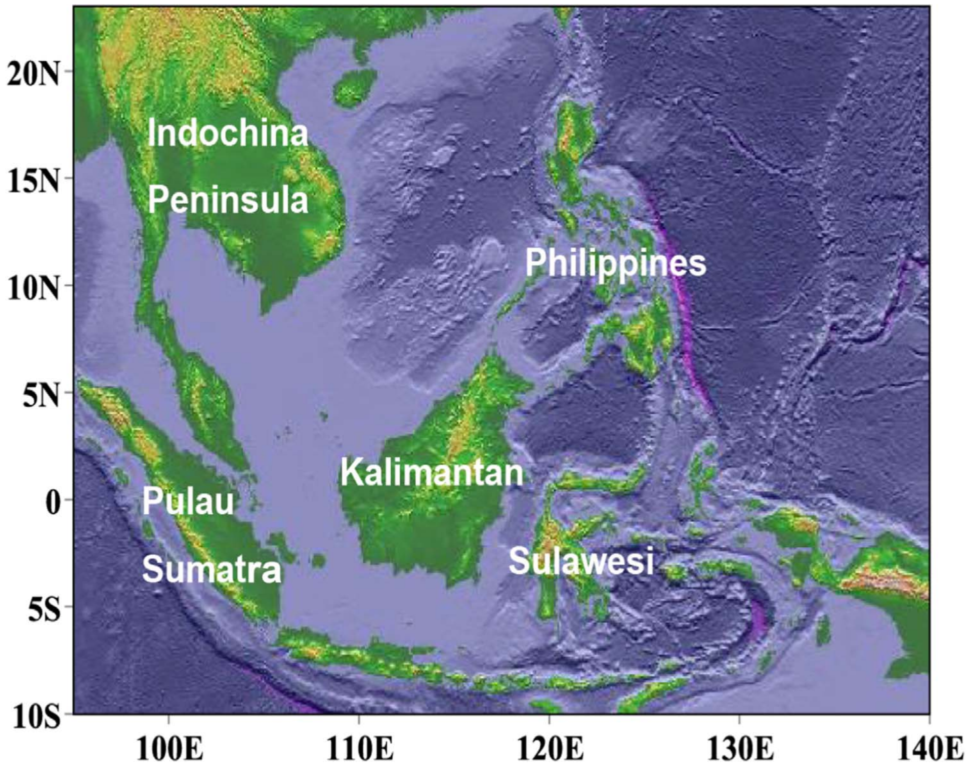

Figure 1. Geographical locations of the main islands in SEA.

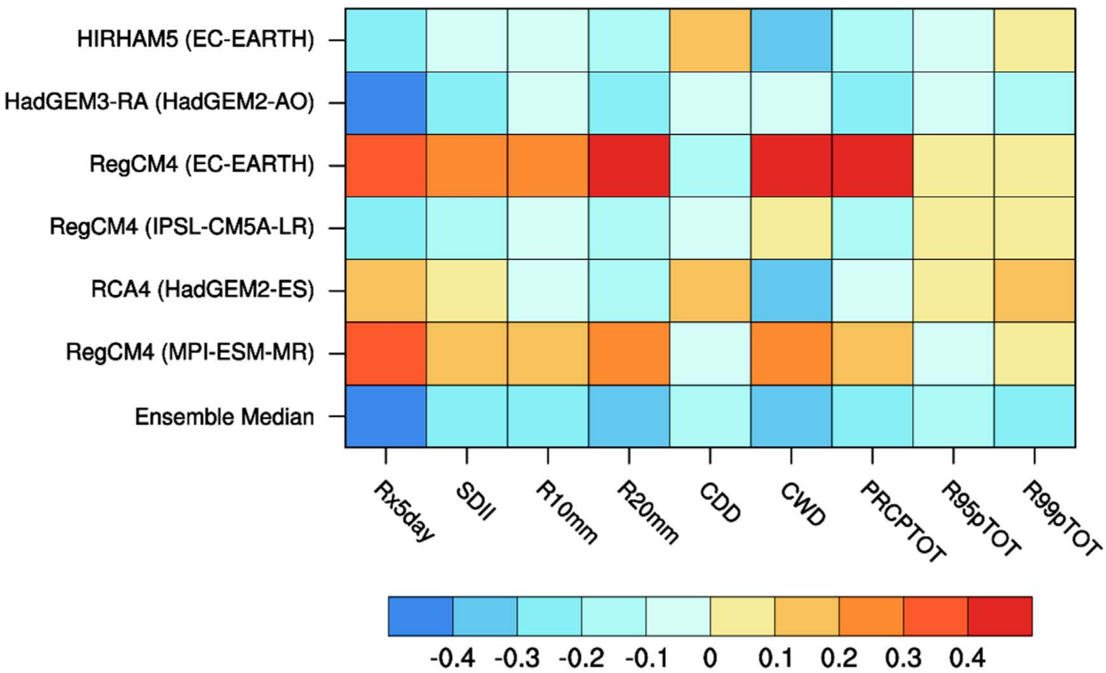

Figure 2. Portrait diagram of relative RMSEs (RMSE′) of extreme precipitation indices simulated by CORDEX models versus observations during the period of 1976–2005.

3. Results

The results are shown in terms of (1) the performance of CORDEX RCM simulated precipitation-based indices compared with observations, (2) the spatial patterns of projected changes of precipitation-based indices for the 1.5 °C and 2 °C GWLs over SEA, the regionally averaged precipitation indices being represented by box-and-whisker plots, and (3) the extreme precipitation changes due to an additional 0.5 °C GWL. The main islands in SEA are shown in figure 1.

3.1. CORDEX RCM evaluation

Figure 2 summarizes the RMSE′ of individual models in simulating the precipitation extremes compared with the reference of APHRODITE observations. The results show that most of the models perform considerably well in simulating most indices with mainly negative RMSE′, especially HIRHAM5 (EC-EARTH), HadGEM3-RA (HadGEM2-AO), RegCM4 (IPSL-CM5A-LR) and RCA4 (HadGEM2-ES). However, the two models RegCM4 (EC-EARTH) and RegCM4 (MPI-ESM-MR) are relatively 'weak' performers, with positive RMSE′ values for all indices except CDD and R95pTOT.

Regarding the model ensemble, to avoid results being influenced by abnormally large model errors (outliers), the median is chosen to represent the deterministic ensemble result rather than the mean value. It is indicated that the ensemble median results perform better than any individual models (figure 2), which eliminates the structural model errors or uncertainties to a great extent (Sillmann *et al* 2013a, 2013b, Zhou *et al* 2014, Han *et al* 2018). Therefore, the ensemble median can be considered to reasonably represent the deterministic results of the multiple future projections.

3.2. Projected changes of precipitation extremes at 1.5 °C and 2 °C GWLs

Figures 3 and 4 present the spatial distributions of projected changes of ensemble medians in precipitation-based indices over SEA at 1.5 °C and 2 °C GWLs, respectively. Except for CWD, the projected changes of extreme precipitation indices at the two GWLs are significantly increased across the Indochina Peninsula (ICP) and Maritime Continent, with disproportionate spatial extents and magnitudes. In particular, larger high-confidence areas of increasing precipitation extremes can be observed at the 2 °C GWL compared with the 1.5 °C GWL. Projected changes at the 1.5 °C GWL indicate partially significant decreases in CWD over parts of the Philippines, Kalimantan and Sulawesi. The prominent decrease of CWD by 1–3 days decreases further under the 2 °C GWL, especially over Kalimantan and Sulawesi. Conversely, the CDD is projected to increase at 1.5 °C and 2 °C GWLs with longer dry spells projected over the whole of SEA. Reduced CWD together with the increased CDD as well as R95pTOT and R99pTOT suggest the precipitation extremes will establish under both GWLs. This is likely to have negative impacts on food security and water availability, especially for the countries in SEA with large coastal population densities. In contrast with CWD, RX5day and SDII indicate a consistent increase at GWLs of 1.5 °C and 2 °C over the whole ICP and Maritime Continent. A higher SDII implies that wet days become wetter and intensified precipitation events may occur more frequently, although the CWD is projected to decrease. R10mm and R20mm are projected to increase constantly with larger magnitudes over Maritime Continent.

To identify the regional response to the two GWLs, the projected percentage changes in the indices (averaged over the land area within SEA) are depicted in figure 5. Indices of heavy precipitation days (R10mm and R20mm) and of extremely wet days (R95pTOT and R99pTOT) show distinctly larger spreads than the other indices with significantly larger uncertainties of the projections of extreme precipitation indices. However, the results show that the ensemble medians of the index changes are all greater than 0, implying increasing trends of all indices compared with the reference period of 1976–2005. The most significant increases show R99pTOT and R95pTOT with magnitudes of 33.4% and 23.7% at the 1.5 °C GWL, and R99pTOT and R20mm with magnitudes of 35.9% and 29.3% at 2 °C GWL. On the other hand, the ensemble medians of PRCPTOT (SDII) increase with minimum magnitudes of 5.0% and 5.8% (5.5% and 7.4%) at 1.5 °C and 2 °C GWLs.

The projected percentage changes of the indices show similar results for a specific island in SEA, for example Kalimantan, as for the whole SEA (figure S1, available online at stacks.iop.org/ERL/14/044015/mmedia). R95pTOT and R99pTOT show a large increase, with magnitudes of 16.0% and 25.6% for their ensemble medians at the 1.5 °C GWL, but with magnitudes of 21.2% and 32.8% at 2.0 °C GWL. CDD increases from 28.7% to 29.9% after the additional 0.5 °C GWL, while CWD shows a slight decrease. Additionally, the increasing rates of the wet and extremely wet-day precipitation are much more abrupt compared with both the total and daily average precipitation of wet days, further confirming the critical risks of extreme precipitation at the GWLs. It is also notable that the changes in precipitation extremes, except CWD, over SEA are generally greater at the 2 °C GWL than the 1.5 °C GWL, which will be further discussed in the next subsection.

3.3. Differences in precipitation extremes between the two GWLs

To further understand the impacts of the additional 0.5 °C GWL on the precipitation indices over SEA, the differences between 2 °C and 1.5 °C GWLs are shown in figure 6. Similar to the spatial patterns (figures 3 and 4), the changes in the regional ensemble median (except for CDD and CWD) indicate a general increase over the ICP and Kalimantan; CDD is projected to decrease over the northwestern mountainous ICP region and increase over most of Maritime Continent and central ICP, while CWD shows a slight reduction over the whole of SEA. Furthermore, the SEA-averaged changes of the ensemble medians are always larger at 2 °C than at the 1.5 °C GWL for all indices except CWD (figure 5). It is also noticed that the most pronounced median change is projected for R20mm,

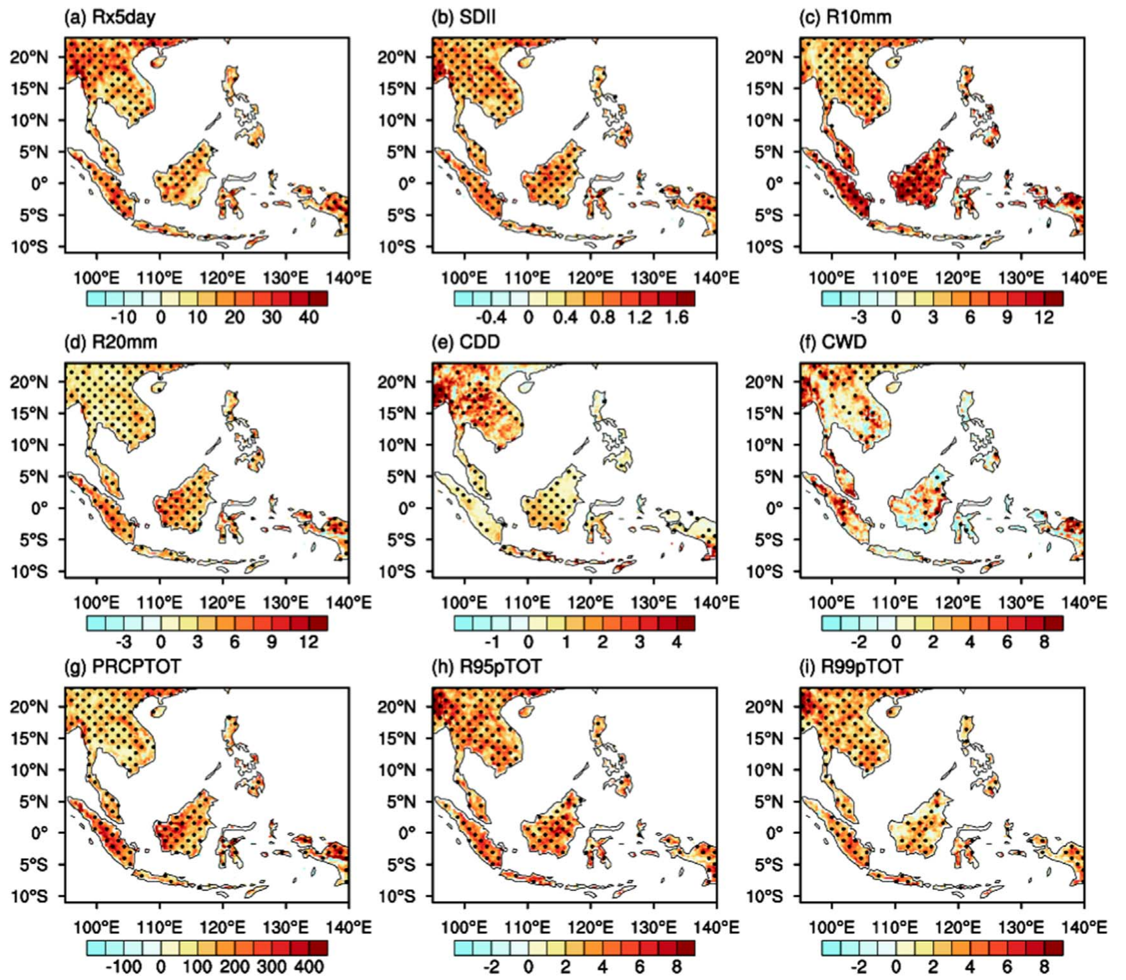

Figure 3. Projected CORDEX ensemble median changes in precipitation extreme indices at the 1.5 °C GWL relative to 1976–2005. The black dots indicate statistical significance at the 95% confidence level. All SNRs are greater than 1 over the area.

with a magnitude increasing from 20.7% at 1.5 °C GWL to 29.3% at 2.0 °C, whereas the CWD ensemble median decreases from 8.7% to 7.6%. Moreover, a larger model spread is generated for all indices at the higher GWL, indicating the larger uncertainty of projections with the additional 0.5 °C GWL.

Figure S2, available online at stacks.iop.org/ERL/14/044015/mmedia shows that the changes in convective precipitation over SEA are responsible for increasing CDD and decreasing CWD, as well as the small changes in R95pTOT and R99pTOT when considering the additional 0.5 °C GWL over the main islands of SEA. That is, convection plays a primary role in precipitation over tropical areas, which concentrates the heavy rainfall locally over a short time scale and tends to bring more extreme precipitation events. It is clearly indicated that the projected convective precipitation changes increase in general over the ICP and Kalimantan with the additional 0.5 °C GWL. Therefore, heavy and extreme precipitation events are expected to increase, especially in R10mm, R20mm and SDII over Kalimantan (figure 6), and extended dry spells and shortened wet spells could be mainly attributed to the enhanced convective precipitation. Moreover, the averaged median changes in convective precipitation relative to the reference period are 7.5% and 8.8% at the 1.5 °C and 2 °C GWLs, respectively. The difference in percentage change of convective precipitation (1.3%) is rather close to those of R95pTOT (1.7%) and R99pTOT (2.4%). However, even for the slight changes in precipitation extremes due to the additional 0.5 °C GWL, the impacts over SEA could be enormous. These results are consistent with the RCM projections over high Alpine elevations, which suggests that increases in extreme precipitation (R95pTOT) over large Alpine areas are affected by enhanced summer convective rainfall, especially in the early and mid-century time slices (Giorgi *et al* 2016). It is also noteworthy that the projected changes in convective precipitation show a slight decrease over the southeastern part of Sumatra. This corresponds well to the decrease of precipitation extreme indices (R10mm, PRCPTOT and CWD) over Sumatra in figure 6, although they are not significant. In general, most changes of the ensemble median in extreme indices indicate enhanced precipitation over SEA varying independently for different islands, suggesting a high sensitivity of precipitation extremes to the additional 0.5 °C GWL.

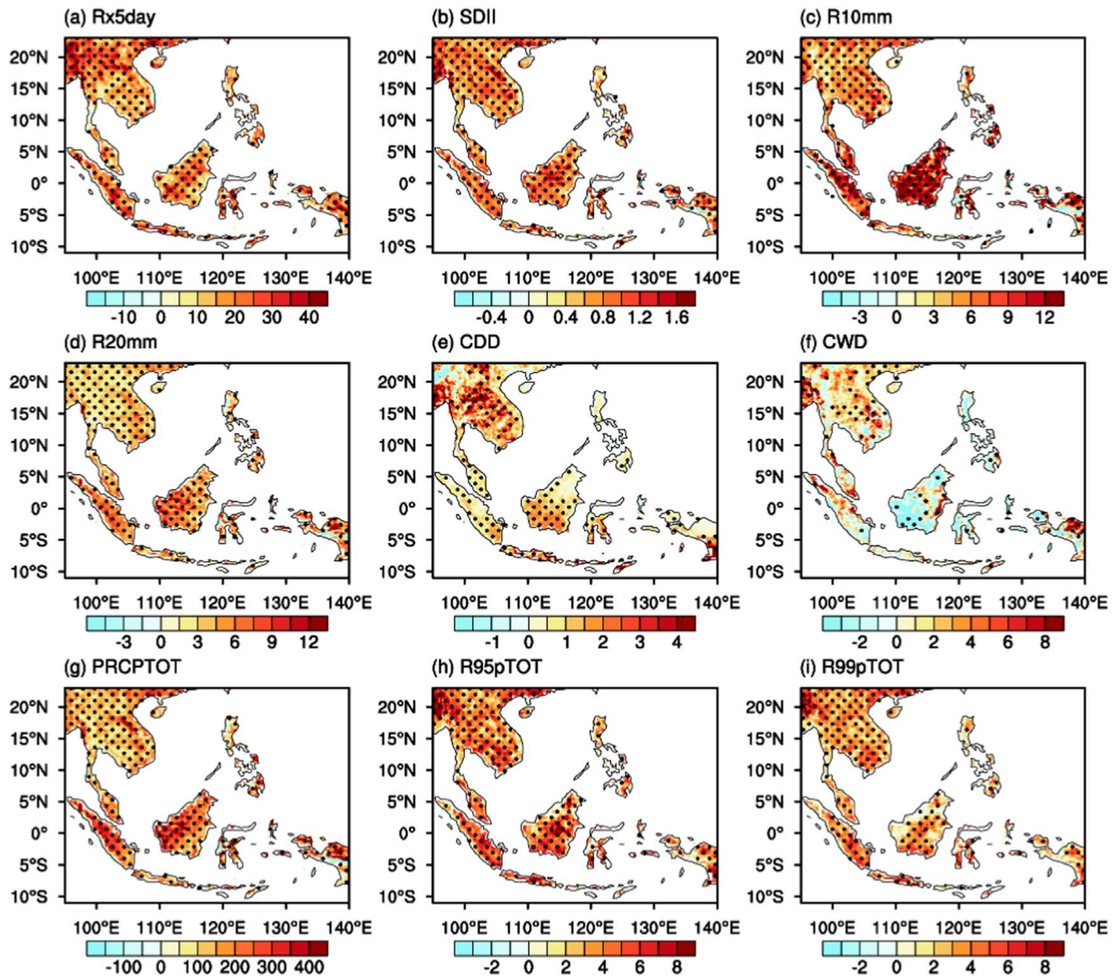

Figure 4. Same as figure 3, but at the 2.0 °C GWL.

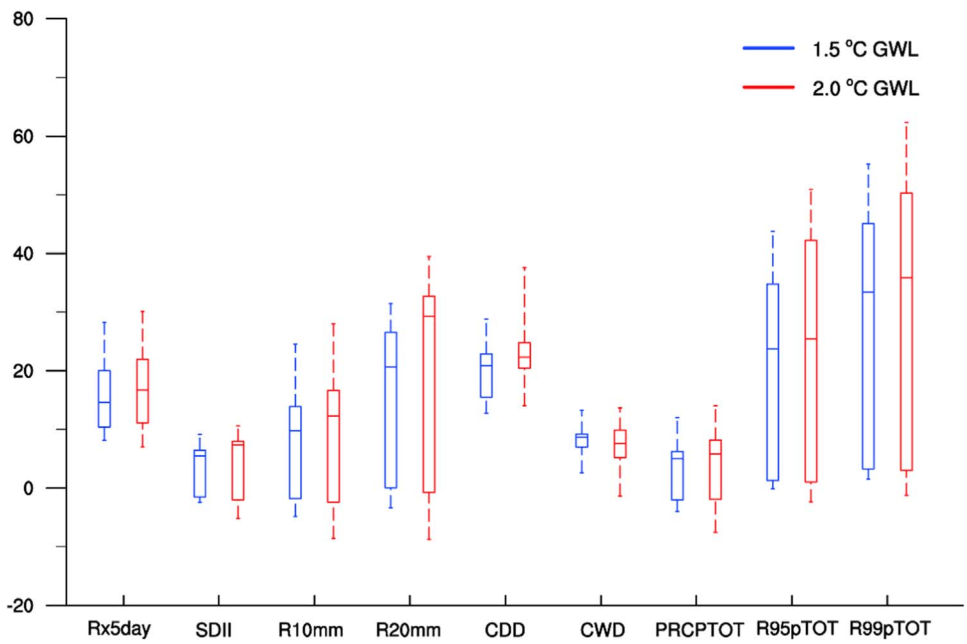

Figure 5. Boxplot of projected changes in percentage of precipitation extreme indices averaged over SEA (land only) for the 1.5 °C (blue) and 2.0 °C (red) GWLs relative to 1976–2005. Boxes indicate the interquartile model spread (25th and 75th quantiles) with the horizontal line indicating the ensemble median and the whiskers showing the extreme range of the ensemble.

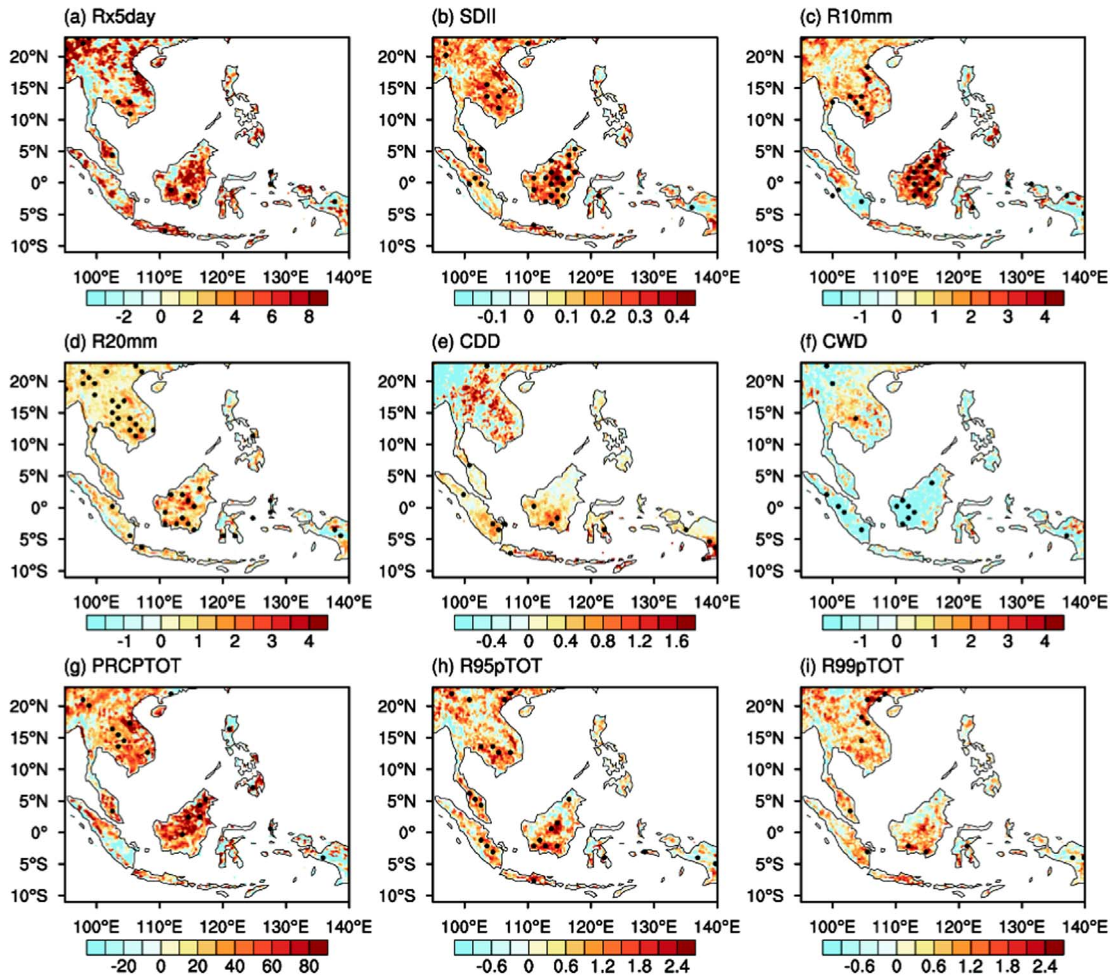

Figure 6. Difference between the changes in the ensemble median for precipitation extreme indices at the 2.0 °C and 1.5 °C GWLs. The black dots indicate statistical significance at the 95% confidence level. All SNRs are greater than 1 over the area.

4. Conclusions and discussion

In this study, we have evaluated projected changes in extreme precipitation-based indices on the ETCCDI (table 2) using the latest available CORDEX simulations covering Southeast Asia (SEA). For the first time, the results provide relatively detailed information on the future precipitation changes expected for countries in the Indochina Peninsula (ICP) and the Maritime Continent with the frequency and intensity of precipitation extremes being strengthened over SEA at both 1.5 °C and 2 °C global warming levels (GWLs). The main findings are summarized as follows:

(i) The ensemble medians of precipitation-based indices, except for CWD, show consistent increases across the ICP and Maritime Continent at both GWLs. Predominant changes in most of the indices are more significant at the 2.0 °C GWL than at the 1.5 °C GWL. From the regionally averaged median changes of the indices, most indices are projected to increase at the 1.5 °C and 2 °C GWLs. The most pronounced increases in the ensemble medians are found in R99pTOT with magnitudes of 33.4% and 35.9% at the 1.5 °C and 2 °C GWLs, respectively. On the other hand, the ensemble medians of PRCPTOT increase with the minimum magnitudes of 5.0% and 5.8% at the 1.5 °C and 2 °C GWLs, respectively. Although the ensemble spreads are relatively large in indices concerning heavy precipitation days and extremely wet days, most of the ensemble models agree with the sign of change, with their SNRs all greater than 1.

(ii) Robust differences in indices of precipitation extremes can be found over SEA for an additional warming of 0.5 °C. Persistent increases are significant for differences between the two GWLs for indices excluding CDD and CWD. CDD is inclined to increase over Maritime Continent and the central ICP but decrease over the other regions, while CWD shows a slight reduction over the whole of SEA. Significant differences in the indices are mainly focused over the Maritime Continent, indicating the high sensitivity of the precipitation extremes to changes in the GWL.

(iii) For the additional 0.5 °C GWL, the most pronounced median change averaged over the SEA is projected in R20mm, with the magnitude increasing from 20.7% to 29.3%, while the changes in CWD are projected to decrease from 8.7% to 7.6%. Global warming at either the 1.5 °C or 2 °C level may have implications for climate vulnerability over SEA. The index evolutions indicate an intense increase in extreme precipitation events over this region in a warmer future.

Restricting warming to 1.5 °C would significantly reduce the regional and local climate risks, including to water resources, food security and agricultural production in developing countries (Huang *et al* 2017, Dosio and Fischer 2018). More recently, we have noticed that the projected changes in annual precipitation amount and extremes at 2 °C GWL are primarily investigated over SEA (Tangang *et al* 2018). These results encourage us to evaluate the projected changes in precipitation extremes at different GWLs. For SEA, our analysis indicates that an additional 0.5 °C global warming leads to an increase in the frequency and intensity of precipitation extremes, which will enhance climatic stress in the densely populated large coastal regions. However, we did not address more complex aspects of the SEA climate projections, for example the variation and variability of summer monsoon rainfall at different GWLs. These essential characteristics over some specific regions are subject of ongoing future analysis.

Furthermore, it is evident that the GWL at (or above) 2 °C will be associated with regional-scale risks of extreme temperature and precipitation more critical than what is obtained for the 1.5 °C GWL (Déqué *et al* 2016, Sillmann *et al* 2017). To better understand the response of climate to different global warming thresholds, the next generation of models (GCMs and RCMs) is needed to provide more details quantifying and assessing the changes of climatological means, variability and extremes.

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