Article

Significant Increase in Population Exposure to Extreme Precipitation in South China and Indochina in the Future

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Abstract: Extreme precipitation events cause severe economic losses and can seriously impact human health. Therefore, it is essential to project possible future changes in the population’s exposure to precipitation extremes against the background of global warming. On the basis of model outputs from phase 6 of the Coupled Model Intercomparison Project, our study shows that both the frequency and intensity of extreme precipitation are likely to increase in the South China and Indochina region in the coming century, especially under the business-as-usual Shared Socioeconomic Pathway (SSP) scenario, SSP5-8.5. The largest population exposure can be expected under the SSP2-4.5 scenario, both in South China and Indochina. If early adoption of mitigation measures via the SSP1-2.6 scenario can be achieved, it may be possible to limit the average population exposure in South China to a relatively low level, while Indochina’s may even be smaller than it is currently. In terms of spatial distribution, the maximum population exposure is most likely to be centered in southern South China. This study also reveals that the contribution of the population–climate interaction to population exposure is likely to increase in the future, and different contributions from the factors of climate and population correspond to different emission policies. Under SSP2-4.5, the importance of climate change and the population–climate interaction is more likely to increase.

Keywords: extreme precipitation; South China; Indochina; CMIP6; population exposure

1. Introduction

During the past few decades, the occurrence of extreme precipitation events has become increasingly frequent in many terrestrial regions [1–3]. Unlike total precipitation, extreme precipitation in both wet and dry regions has shown robust increases over the past few decades, which can be seen from observations and climate models [4]. However, Papalexiou and Montanari indicated that the increasing trend of extreme precipitation frequency is highly unlikely under the assumption of stationarity [5]. In other words, the increase of extreme precipitation frequency is nonstationarity. The increase in extreme precipitation has exerted adverse impacts on ecosystems, economies, and human health [3,6]. This is especially the case for South China and Indochina (INCSC), a region vulnerable to extreme precipitation hazards, such as widespread flooding, due to the influences of monsoon systems, complex topography, and its large population [7,8]. For example, severe flooding in the coastal city of Guangzhou in 2017 caused huge economic losses and numerous injuries [9]. Therefore, assessing future risks, especially the vulnerability of populations to extreme precipitation, is important for risk management strategies and sustainable development.

Based on the sixth national census, Jiang et al. projected the future population under five Shared Socioeconomic Pathway (SSP) scenarios for China by setting up a series of parameters (e.g., fertility and migration) in the Population Development-Environment...
(PDE) model. Results show that the population of China will grow until 2035 and then decline until 2100 under the five SSPs. Moreover, the maximum population by 2100 is expected to be in Guangxi province in China under SSP3 [10]. Faced with the threat of a continual increase in climate extremes, the future exposure of populations to extreme precipitation has been projected to increase worldwide during the 21st century [11–17]. Based on phase 5 of the Coupled Model Intercomparison Project (CMIP5) multimodel projections, Zhang and Zhou [3] reported that the exposure of populations to extreme precipitation events in the populous global land monsoon regions would increase consistently against the background of global warming. Additionally, driven by the ever-changing climate and rapid population growth rate, the average exposure worldwide of populations to extreme drought is also projected to increase about 4-fold by the end of the 21st century under the Representative Concentration Pathway (RCP) 8.5 scenario [16]. For China, although its population is expected to decrease, the aggregate exposure increases by about 21.6% under the RCP4.5 scenario by the end of the 21st century [14]. The changes in population exposure in Indochina in the future have been relatively less reported when compared to other regions in the world. However, considering that the extreme precipitation events in the INCSC region may occur more frequently in the future [18], the changes in the exposure of populations to these precipitation extremes are also worthy of investigation.

A new and more reasonable organizational structure was adopted in phase 6 of the Coupled Model Intercomparison Project (CMIP6) [19]. The CMIP6 models generally have finer resolutions [19] and better simulation of climate extremes compared with CMIP5 models [20–21]. However, to date, the future changes in the exposure of populations to precipitation extremes in the INCSC region have not yet been projected in CMIP6 multimodel simulations, which is the main goal of this study. The relative importance of climate and population in causing these changes in exposure is also discussed. Such information is important for understanding future vulnerability and crucial for risk assessment and adaptation strategies.

The structure of the paper can be summarized as follows. Section 2 introduces the data and methods. The changes in extreme precipitation and population exposure and the contribution of different factors to population exposure are described in Section 3. Section 4 provides some discussion, and Section 5 presents the conclusions.

2. Data and Methods

2.1. The Study Area

In this study, the INCSC region is defined as the mainland from 0–30° N and 90–120° E and mainly includes Myanmar, the Malaysian Peninsula, Thailand, Laos, Cambodia, Vietnam, and South China (Figure 1). The terrain of the INCSC region includes mountains and plateaus and is generally high in the north and low in the south. The INCSC region is surrounded by the ocean on three sides and is extremely susceptible to extreme precipitation [18]. The INCSC region is densely populated, with more than half of the population living within 100 km of the coastline. Therefore, extreme precipitation changes may have a great impact on the population exposure of this region.

2.2. Data

2.2.1. CMIP6 Model Output

In this study, 26 CMIP6 models (Table 1) are used [19,22]. The daily precipitation data from CMIP6 historical simulations (1995–2014) and future projections (2015–2100) under 3 SSPs, including SSP1-2.6, SSP2-4.5, and SSP5-8.5, are analyzed. As a combination of the RCPs and alternative pathways of socioeconomic development [16,19], SSP1-2.6 envisions the sustainable pathway, while SSP2-4.5 and SSP5-8.5 represent the central pathway and business-as-usual pathways, respectively.
Table 1. CMIP6 models used in the study.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Atmospheric Resolution (lat × lon)</th>
<th>Country</th>
<th>Source Link</th>
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<td>ACCESS-CM2</td>
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<td>Australia</td>
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</table>

2.2.2. Population Data

The observed populations in 2010 for South China and Indochina are from the sixth national census of China and the World Bank, respectively. The International Institute
for Applied Systems Analysis (IIASA) provided the projected national populations from 2011 to 2100 under the 3 SSPs. On this basis, Jiang et al. [10] adjusted the parameters of population and economic forecasting models adopted by IIASA and obtained an updated projected national population dataset from 2011 to 2100 [10]. With strict quality control, this updated dataset has been used extensively in previous studies [3,10]. In this study, the observed and projected populations described above were used to calculate the current and future population exposure.

Figure 1. Geographical location and altitudes (shading, unit: m) of the INCSC region.

2.3. Extreme Precipitation Indices

The extreme precipitation threshold can be calculated based on the percentiles method. The details of the percentiles method can be obtained in Tang et al. [18] and Zhai et al. [23]. Additionally, the percentiles method has been widely adopted in previous studies [24–31]. Based on this extreme precipitation threshold, two extreme precipitation indices, extreme precipitation days (R95d) and extreme precipitation intensity (AEPI), are calculated (Table 2). R95d is defined as the number of days in a year on which the daily precipitation is greater than the extreme precipitation threshold, and AEPI can be obtained by dividing the total amount of extreme precipitation by the extreme precipitation days in a year. These two indices are employed to characterize the frequency and intensity of extreme precipitation [32–36]. In this study, these extreme precipitation indices are first computed for different models on their original grids and then interpolated to a common $1^{\circ} \times 1^{\circ}$ grid using bilinear interpolation [37–40].
Table 2. Abbreviations, descriptive names, and definitions of extreme precipitation indices used in this study.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Descriptive Name</th>
<th>Definition</th>
<th>Unit</th>
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<td>R95d</td>
<td>Extreme precipitation days</td>
<td>The number of days in the year when the daily precipitation exceeds the extreme precipitation threshold.</td>
<td>day</td>
</tr>
<tr>
<td>AEPI</td>
<td>Extreme precipitation intensity</td>
<td>Intensity of extreme precipitation. AEPI = total precipitation amount when the daily precipitation exceeds the extreme precipitation threshold/R95d.</td>
<td>mm day$^{-1}$</td>
</tr>
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</table>

2.4. Methods

2.4.1. Population Exposure

As universally defined in previous studies, our measure of population exposure is the number of individuals exposed to extreme precipitation. That is, extreme precipitation days multiplied by the corresponding population on each grid cell for the specified period [41]. Note that the population in 2010 was regarded as the population in the historical period.

2.4.2. Contributing Factors to Changes in Population Exposure

As shown in Jones et al. (2015) [41], the change in population exposure ($\Delta E$) can be decomposed into three parts as follows:

$$\Delta E = C_1 \times \Delta P + P_1 \times \Delta C + \Delta P \times \Delta C,$$

in which $C_1$ is the average number of extreme precipitation days during 1995–2014 and $P_1$ is the population in 2010. Then, $\Delta C$ and $\Delta P$ correspond to the associated changes in extreme precipitation days and population under three SSPs with respect to the baseline, which means 1995–2014 and 2010, respectively. Therefore, $C_1 \times \Delta P$, $P_1 \times \Delta C$, and $\Delta P \times \Delta C$ represent the influence of the change in population, climate, and population–climate interaction, respectively.

The contribution rates of changes in each factor can be calculated as follows:

$$CR_{\text{pop}} = \frac{C_1 \times \Delta P}{\Delta E} \times 100\%;$$  

$$CR_{\text{cli}} = \frac{P_1 \times \Delta C}{\Delta E} \times 100\%;$$ 

$$CR_{\text{int}} = \frac{\Delta C \times \Delta P}{\Delta E} \times 100\%.$$

Here, $CR_{\text{pop}}$, $CR_{\text{cli}}$, and $CR_{\text{int}}$ represent the contribution rates of changes in population, climate, and population–climate interaction, respectively.

3. Results

3.1. Changes in Extreme Precipitation

Before conducting the future projection, the CMIP6 model performance in simulating spatial-temporal variation of R95d and AEPI was firstly evaluated [32]. In general, the CMIP6 multimodel ensemble mean (MME) can reasonably reproduce the spatial-temporal variation of the frequency and intensity of extreme precipitation, although most of the models overestimate these two indices in Cambodia and southern Myanmar. Relatively speaking, the performance of most CMIP6 models in South China is better than that in Indochina. For the future projection of extreme precipitation indices, all the models are assigned with equal weights.

With continuous warming expected in the future, the CMIP6 MME presents a consistently increasing trend for R95d and AEPI in the INCSC region. However, the change varies among different scenarios, especially after 2050 (Figure 2). For example, R95d in
2081–2100 shows an increase of less than 20% under SSP1-2.6 and SSP2-4.5, but up to 40% under SSP5-8.5 in Indochina (Figure 2c). Meanwhile, R95d increases more than AEPI in both South China and Indochina by the end of the 21st century under the 3 SSPs, especially under SSP5-8.5. The increase in R95d in South China by the end of the 21st century under SSP5-8.5 may exceed 20%, but only about 10% for AEPI (Figure 2a,b). This means that the frequency of extreme precipitation is expected to increase more than the intensity by the end of the 21st century under the 3 SSPs in the INCSC region. Take note that if the early adoption of mitigation policies via SSP1-2.6 can be achieved, the increase in the intensity of extreme precipitation in the INCSC region is expected to remain almost stable starting in 2050 (Figure 2b,d).

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Changes in the (a,c) frequency and (b,d) intensity of extreme precipitation averaged over (a) South China and (b) Indochina, calculated from phase 6 of the Coupled Model Intercomparison Project (CMIP6) ensembles under different Shared Socioeconomic Pathway (SSP) scenarios relative to the baseline (1995–2014). Solid lines represent the ensemble average, and the shaded areas indicate the projection uncertainty characterized by inter-quartile ensemble spread. A 9−year running mean is applied to the changes.

In terms of spatial distribution, the regions with the largest increase in R95d under the 3 SSPs in the mid-21st century are mainly located in Myanmar, the Malay Peninsula, and Cambodia (Figure 3a–c). For AEPI, the largest increase under the 3 SSPs occurs in Cambodia (Figure 3d–f). Compared with SSP1-2.6 (Figure 3a,d), the changes in R95d under the SSP5-8.5 scenario are not very different (Figure 3c), but AEPI increases rapidly (Figure 3f). This implies that as greenhouse gas emissions rise, the extreme precipitation intensity is more likely to increase than the frequency by the mid-21st century in the INCSC region. Moreover, over 80% of CMIP6 models agree with this conclusion. In other words, early adoption of mitigation policies could probably slow the intensity increase in extreme precipitation in the INCSC region by the mid-21st century.

As can be seen from Figure 4, achieving and maintaining early adoption of mitigation policies will be critical to reducing the probability of increased frequency and intensity of extreme precipitation by the late 21st century. The increases in both R95d and AEPI by the late 21st century are consistently larger than those by the mid-21st century under the same scenario. For R95d, Cambodia is consistently the region with the largest increase under the 3 SSPs (Figure 4a–c), while for AEPI, the largest increase under the 3 SSPs is in Myanmar (Figure 4d–f). This implies that Cambodia is more likely to be at risk of
an increase in extreme precipitation frequency, while Myanmar is more likely to face an increase in extreme precipitation intensity. In addition, the high emissions under SSP5-8.5 consistently produce the greatest increase in both extreme precipitation frequency and extreme precipitation intensity by the end of the 21st century (Figure 4c,f), while the early adoption of mitigation via the SSP1-2.6 scenario shows the smallest increase (Figure 4a,d). Therefore, the implementation of an emissions reduction policy is crucial for the INCSC region to reduce the risk of flooding.

Figure 3. Projected changes in the (a–c) frequency (unit: days) and (d–f) intensity (unit: mm/day) of extreme precipitation in 2041–2060 under 3 SSPs relative to the baseline (1995–2014): (a,d) SSP1-2.6; (b,e) SSP2-4.5; (c,f) SSP5-8.5. The areas with slanted lines indicate where more than 80% of the models show the same sign of the changes in the multimodel ensemble mean (MME).

Figure 4. As in Figure 3, but in 2081–2100.
Briefly, extreme precipitation in the INCSC region will be more intense and frequent in the future under 3 SSPs, especially under the business-as-usual SSP5-8.5 scenario. Thus, a key issue is raised here in terms of the effects of increasing frequency and density of extreme precipitation on the human population. To address this issue, the likely future changes in the exposure of populations to precipitation extremes under different scenarios are explored in the following section.

3.2. Changes in Population Exposure

The projected population exposures to precipitation extremes averaged in the INCSC region are given in Figure 5. The largest population exposure in the INCSC region can be expected under the central pathway (Figure 5c,d), whereas the largest magnitude of the increase in precipitation extremes is more likely to occur under the SSP5-8.5 scenario (Figure 4c,f). Under the 3 SSPs, the projected population exposures to precipitation extremes in the INCSC region increase rapidly before the 2050s but thereafter slow down or decline. Besides, some differences exist in the change in population exposure between South China and Indochina. In South China, the population exposure shows progressive increases from the current period to the 2100s under SSP2-4.5, with a larger magnitude than that under SSP1-2.6 and SSP5-8.5 (Figure 5c). For Indochina, the population exposure to precipitation extremes first increases before the mid-21st century and then decreases after that under the 3 SSPs (Figure 5b–f). The projected population exposure to extreme precipitation in the INCSC region under the SSP1-2.6 scenario by the end of the 21st century is almost equal to or smaller than that currently, which means that reduced emissions can effectively reduce the population exposure to extreme precipitation in both South China and Indochina.

**Figure 5.** Population exposure to extreme precipitation from 2010 to 2100 averaged over (a,c,e) South China and (b,d,f) Indochina under 3 SSPs: (a,b) SSP1-2.6; (c,d) SSP2-4.5; (e,f) SSP5-8.5. Unit: million person-day.
Briefly, the largest population exposure to precipitation extremes can be expected under the SSP2-4.5 scenario both in South China and Indochina, with the population exposure in the former expected to be larger than that in the latter. If early adoption of mitigation via the SSP1-2.6 scenario can be achieved, the population exposure in South China can be limited to a relatively low level, and the population exposure in Indochina could even be smaller than the current level.

Figures 6 and 7 display the projected population, population exposure in the mid and end of the 21st century, and the relative change in population exposure in the mid and end of the 21st century relative to the baseline (1995–2014) across the INCSC region (population exposure in the mid or end of the 21st century minus the population exposure during 1995–2014). In the mid-21st century (Figure 6), the spatial distribution of exposure (Figure 6d–f) generally shows a similar pattern to the population (Figure 6a–c), with maximum exposure located in southern South China. The relative change in population exposure can be clearly seen in Figure 6g–i. The population exposure is expected to increase in almost the whole of the INCSC region under the 3 SSPs, except in some parts of northeastern South China under SSP5-8.5 (Figure 6i). The population, population exposure at the end of the 21st century, and relative change relative to the baseline (1995–2014) are shown in Figure 7, in which the results exhibit little difference compared with those in the mid-21st century.

Figure 6. Projected (a–c) population (unit: million people), (d–f) population exposure (unit: million people per day) in the future period (2041–2060), and (g–i) the relative change in population exposure [population exposure from 2041 to 2060 minus that during 1995–2014 (unit: million person-day)] under different SSPs: (a,d,g) SSP1-2.6; (b,e,h) SSP2-4.5; (c,f,i) SSP5-8.5.
As shown above, the population exposure, both in the mid and end of the 21st century, is expected to increase in nearly the whole of the INCSC region, with maximum exposure centered in southern South China.

3.3. Contribution of Different Factors to Population Exposure

The relative importance of three factors, including climate, population, and population–climate interaction, to the projected population exposure in the INCSC region is presented in Figure 8. An obvious increase in the population–climate interaction factor can be detected from the 2020s to 2100s in both South China and Indochina under the 3 SSPs. As a result, the sum of the contributions of climate and population shows a declining trend. However, the relative importance of climate and population to the change in population exposure shows different features under different future scenarios. Under SSP1-2.6, the contribution of climate to population exposure in South China around the 2050s is basically equal to that of the 2020s, while the contribution of population decreases. In the 2100s, however, the contribution of climate decreases compared with that of the 2020s, and the contribution of population gradually increases (Figure 8a). For Indochina, climate change contributes approximately 50% to the population exposure in the 2070s, which is larger than that of population. Later, in the 2100s, the contribution of population change is much greater than that of climate change (Figure 8b). As for SSP2-4.5, the contribution of climate in South China changes little from the 2020s to the 2100s, while the contribution of population gradually decreases (Figure 8c). The effects of climate change in Indochina show a uniform, increasing trend, whereas the impact of population change decreases...
from the 2020s to the 2100s (Figure 8d). Under SSP5-8.5, the contribution of population changes to population exposure in 2081–2100 in the INCSC region is smaller than that in the current period (Figure 8e,f). The impact of climate change does not change much in South China (Figure 8e) but rises first and then decreases in Indochina (Figure 8f). In short, the contribution of the population–climate interaction factor tends to increase in the future, while different contributions from climate and population to population exposure correspond to different emission policies. Under SSP2-4.5, the importance of the climate factor and population–climate interaction factor is more likely to increase in the future.

Figure 8. Contributions from changes in climate (blue), population (green), and their interaction (orange) to population exposure in (a,c,e) South China and (b,d,f) Indochina in the future under 3 different SSPs: (a,b) SSP1-2.6; (c,d) SSP2-4.5; (e,f) SSP5-8.5. Unit: %.
4. Discussion

This work analyzes future projections of population exposure to extreme precipitation in the INCSC region on the basis of the latest CMIP6 simulations. It shows that substantial changes in population–climate interaction will likely play an important role in population exposure, which further implies that early adoption of mitigation policies is crucial for reducing the exposure of populations to extreme precipitation in the future. This finding can serve as a useful reference for policymaking in terms of both emissions reduction and population growth control toward sustainable development in the INCSC region in the future.

However, a limitation of this study should also be noted. First, the extreme precipitation indices simulated by CMIP6 models, broadly speaking, exhibit biases compared with observed data, meaning that biases may exist in the projected population exposure also. To validate the robustness of the projection results, the application of regional climate models, which by definition are higher resolution, is worthy of further investigation. More population datasets are also needed to validate the robustness of our results since only one set of population data was used in this study. Second, a simple multi-model ensemble mean was used for future projection. Adopting a rank-based weighting method for future projection of population exposure is a good choice for the reduction of the uncertainties. Moreover, this study mainly focuses on impact-relevant extremes and population exposure to precipitation extremes, while changes in the water cycle and land use may also have substantial influences on population exposure. The impact of changes in the water cycle and land use on population exposure will be considered in our future work. At last, it should be mentioned that there is a strong need for further validation of the results obtained in this study.

5. Conclusions

This study analyzes the population exposure to precipitation extremes in the INCSC region in the future and investigates the relative importance of climate and population to the likely future changes in population exposure on the basis of CMIP6 multimodel projections under 3 SSPs (SSP1-2.6, SSP2-4.5, and SSP5-8.5). The main conclusions are as follows:

(1) Extreme precipitation events in the INCSC region will be more intense and frequent under the 3 SSPs, especially under the business-as-usual scenario of SSP5-8.5. Early adoption of mitigation policies could probably slow the increase in extreme precipitation intensity in the INCSC region by the mid-21st century, as well as reduce the probability of both increased intensity and frequency of extreme precipitation by the end of the 21st century.

(2) There is expected to be a significant increase in population exposure to precipitation extremes in the INCSC region, and the largest population exposure can be expected under the SSP2-4.5 scenario. If early adoption of mitigation via the SSP1-2.6 scenario can be achieved, the average population exposure in South China can be limited to a relatively low level, while that in Indochina may even be smaller than it is currently. In terms of spatial distribution, the largest population exposure under the 3 SSPs is projected to be centered in southern South China, both in the middle and end of the 21st century.

(3) As two pivotal factors, the frequency of extreme precipitation and the size of the human population can affect the exposure of that population to precipitation extremes. It is revealed in this study that the contribution of the population–climate interaction is likely to increase in the future, while different contributions from climate and population to population exposure correspond to different emission policies. Under SSP2-4.5, the importance of climate change and population–climate interaction is more likely to increase in the future.
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