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How Striking Is the Intergenerational Difference in Exposure to Compound Heatwaves Over Southeast Asia?

Xuerong Sun[1], Fei Ge[1], Quanliang Chen[1], Klaus Fraedrich[2], and Xing Li[1]

[1]School of Atmospheric Sciences, Plateau Atmosphere and Environment Key Laboratory of Sichuan Province, Joint Laboratory of Climate and Environment Change, Chengdu University of Information Technology, Chengdu, China, [2]Max Plank Institute for Meteorology, Hamburg, Germany

Key Points:

- Compound heatwaves are projected to increase substantially by the end of the 21st century, and will no longer be rare events
- The intergenerational differences in exposure to compound heatwaves are gradually widening
- The principal effects responsible for the dramatic increase in population exposure to compound heatwaves vary by age

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

F. Ge,
figo@cuit.edu.cn

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Abstract Southeast Asia (SEA) is experiencing rapid warming, leading to more extreme heatwaves. Sustained compound heatwaves, with high temperatures during day and at night, pose profound threats in highly vulnerable regions, resulting in great stress on society. We estimated the changes in the compound heatwave characteristics and population exposure over SEA at the end of the 21st century based on the model outputs from the Coupled Model Intercomparison Project Phase 6. Results show that the projected compound heatwaves have significant intensified over SEA linked to increasing greenhouse gas emissions. Contemporary younger generations will face more potential risks than their parents' generation. A child born in the 2010s will experience 1,000 discrete heatwaves in their lifetime, a threefold increase compared with the 1980s. Climate change and population growth combine to drive increased population exposure. The climate effect accounts for 125% in the 0–24-year-old cohort, whereas the interaction effect accounts for 85% in the 75+ age group. The relative importance of effects evolves dynamically across age groups, gradually shifting from a predominance of climate effects to a synergy of the climate and population effects. Significant regional inequalities exist in the increased population exposure over SEA. The largest increase occurs in Indonesia, where the aggregate exposure ranges from 45 billion person-days under the SSP1-2.6 scenario to 81 and 108 billion person-days, respectively, in the higher SSP2-4.5 and SSP5-8.5 scenarios. The study emphasizes the need for the SEA countries to focus on heat-stress adaptation strategies, while also working toward fulfilling emission reduction commitments.

Plain Language Summary Heatwaves pose significant risks to public health, the economy and the ecological environment. The impacts of compound heatwaves, which combine blazing days with sultry nights, are greater than those of daytime- or night-time-only heatwaves. Focusing on six Southeast Asian countries at different levels of development, we estimated the number of heatwaves experienced by people spanning different generations over their lifetime, and decomposed the future changes in the population exposure of different age groups. Our results show that the 2010-generation will experience three times as many compound heatwaves as those born in 1980, which is not only an order of magnitude increase but it will become more extreme when extending the time span. For high- to middle-income countries, such as Singapore and Thailand, the exposure of older people will increase significantly in the future as the population ages. The study highlights the imperativeness for urgent actions required to reduce the future effects of compound heatwaves in SEA.

1. Introduction

How bad would unrestricted emissions of greenhouse gases (GHG) be? The global climate has changed significantly over the last century, with major characteristics of warming and a rise of 1.2 ± 0.1°C for the mean surface temperature of between 1880 and 2020 (WMO, 2021). One of the consequences of global warming is the increased risk of exceptionally high temperatures and heatwaves (Hulley et al., 2020; IPCC, 2018; Perkins-Kirkpatrick & Gibson, 2017; Visser et al., 2014). Increasing of weather and climate extremes concurrent with climate-related hazards to public health has become the focus of societal concerns (Anderson & Bell, 2009; Forzieri et al., 2017; Mitchell, 2021). Intensified extreme heat events are expected to occur more frequently and with longer durations by the middle of the 21st century, especially in regions with uneven development of aging societies (Bennett et al., 2014; Bindoff et al., 2013; McMichael et al., 2006; Sun et al., 2022). For example, increased heat extremes will amplify their negative impacts on human survival and development through the exacerbation of health-care burden and heat-related disease risks, such as cardiovascular disorders or respiratory disease (Carleton & Hsiang, 2016; Gasparrini et al., 2015; Sarangi et al., 2021). If no action is taken, population expansion and

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economic development will lead to higher GHG emissions enhancing greater climate warming and destruction of other environmental systems. Projecting future changes in the Earth's climate and their impacts is therefore crucial in the design of specific climate response strategies and mitigation policies.

Southeast Asia (SEA) is a diverse region, comprising 11 countries with a total population >600 million, and an increasing influence on geopolitics (Dong et al., 2021). Undergoing rapid economic, environmental and demographic change maybe one of the most important development challenges facing the region (Weiss, 2009). The frequency of weather and climate extremes has shown an upward trend during the last several decades (Ge et al., 2019; Sun et al., 2022). The Asian–Australian monsoon (Chang et al., 2005; Chevuturi et al., 2018; Ge et al., 2021b; Wang et al., 2004) and the El Niño–Southern Oscillation (Ge et al., 2017; Juneng & Tangang, 2005; Lin & Qian, 2019; Thirumalai et al., 2017) significantly modulate the climate conditions over the SEA mainland—for example, precipitation and temperature in Indonesia are mainly associated with the cycle of the El Niño–Southern Oscillation and its signal is especially strong in areas with a monsoonal climate (Irawan, 2002). SEA has already suffered extreme heatwaves in the last few decades, imposing widespread heat stress and heat disorders that have resulted in considerable economic damages and social consequences (Ge et al., 2021a; IPCC, 2013, 2021; Sun et al., 2022). In April 2016, record-breaking heatwaves led to many deaths and massive socioeconomic loss over SEA (Naveendrakumar et al., 2019). Thailand experienced its hottest summer of the past 65 years, with maximum temperatures exceeding 40°C on most days and temperatures peaking at 44.6°C during the hottest time of the day (Asian Correspondent Staff, 2016). Despite growing evidence of the detrimental impacts on human heath of extremely hot days or nights due to their high intensity and/or prolonged duration, their concurrent occurrence within 1 day (i.e., compound heatwaves) has received much less attention. Compound heatwaves may lead to more significant and widespread risks to human society and ecosystems than either hot days or hot nights in isolation, especially in regions with a dense population (Y. Chen & Zhai, 2017; Horton et al., 2016; IPCC, 2012; Mukherjee & Mishra, 2018). Specifically, there is no doubt that the health effects of hot days are intuitive, but the ensuing night-time heat extremes prevent humans recovering from the preceding daytime heat stress and interfere with normal physiological sleep, resulting in excess morbidity and mortality (He et al., 2022; Hulley et al., 2020; Jiang et al., 2019; Ullah et al., 2019). The ongoing climate crisis will cause compound heatwaves more acute and challenging in terms of their physical impacts on human well-being, their livelihoods and the ecosystem.

Exposure to extreme events can be increased by both climate change and the direct anthropogenic impact on sustainability of rapidly growing settlements in areas with highly concentrated populations (Baker et al., 2018; Batibeniz et al., 2019; Iyakaremye et al., 2021). Additionally, large economic disparities and a rapidly aging population in SEA have given rise to greater threats to health from heatwaves (Chambers, 2020; Habeeb et al., 2015; Lissner et al., 2012). Exposure to dangerously high temperatures jeopardizes both human health and social development, driving increase in morbidity and mortality and reduction in labor productivity and economic output. The threats from the accelerating climate change mean that the future exposure to compound heatwaves is projected to exhibit a significant growth worldwide during the 21st century. An estimation of exposure of populations to future extreme events under different climate scenarios and fertility rates require comprehensive consideration of both climatic and demographic factors. Human exposure to future compound heatwaves is projected to be aggravated by the concurrent changes in both temperature increases and the demographic growth. It is therefore vital for national or individual groups to assess future changes in population exposure to heatwaves. The assessment of future exposure to compound heatwaves plays a fundamental role in recognizing societal impacts and future vulnerability and is crucial to response options of extreme heat events and strategic planning of environmental sustainability.

Coordinated climate model intercomparisons supported by the Coupled Model Intercomparison Project (CMIP) have been at the center of international climate simulations and future projections, as well as those conducted by the scientific community (Kim et al., 2020a). The CMIP is now in its sixth phase, and provides a collection of experimental design focused on specific science questions, and a new set of future forcing targets: the Shared Socioeconomic Pathway (SSP) scenarios (O'Neill et al., 2016). Coupled Model Intercomparison Project Phase 6 (CMIP6) coordinated experiments provide an improved understanding of the Earth's physical processes, showing inclusion of socioeconomic developments, technological advances, and other environmental factors (Eyring et al., 2019; Gidden et al., 2019; Zelinka et al., 2020). As a result, CMIP6 models are expected to minimize possible bias compared with their predecessors and thus improve the reliability of future projections of the regional climate and environment to a greater extent (Grose et al., 2020). It is now a timely opportunity to evaluate the intergenerational differences in exposure to compound heatwaves over SEA. This study selected four heatwave

Table 1
Basic Information of Used Coupled Model Intercomparison Project Phase 6 Models

Model	Institution/country	Resolution (Lon × Lat) (°)	References
ACCESS-CM2	ACCESS (Australia)	1.875 × 1.25	Bi et al. (2020)
ACCESS-ESM1-5	ACCESS (Australia)	1.875 × 1.25	Ziehn et al. (2020)
AWI-CM-1-1-MR	AWI (Germany)	0.94 × 0.94	Semmler et al. (2020)
BCC-CSM2-MR	BCC (China)	1.125 × 1.125	Wu et al. (2019)
CanESM5	CCCMA (Canada)	2.81 × 2.81	Swart et al. (2019)
CMCC-CM2-SR5	CMCC (Italy)	1.25 × 1.0	Cherchi et al. (2019)
CMCC-ESM2	CMCC (Italy)	1.25 × 1.0	Cherchi et al. (2019)
CNRM-CM6-1	CNRM-CERFACS (France)	1.41 × 1.41	Voldoire et al. (2019)
CNRM-ESM2-1	CNRM-CERFACS (France)	1.41 × 1.41	Séférian et al. (2019)
EC-Earth3	ICHEC (Europe)	0.70 × 0.70	Massonnet et al. (2020)
EC-Earth3-Veg	ICHEC (Europe)	0.70 × 0.70	Wyser et al. (2020)
GFDL-ESM4	GFDL-NOAA (USA)	1.25 × 1.0	Held et al. (2019)
INM-CM4-8	INM (Russia)	2.0 × 1.5	Volodin et al. (2018)
INM-CM5-0	INM (Russia)	2.0 × 1.5	Volodin et al. (2017)
IPSL-CM6A-LR	IPSL (France)	2.50 × 1.26	Boucher et al. (2020)
KIOST-ESM	KIOST (Korea)	1.87 × 1.87	Kim et al. (2020b)
MIROC6	MIROC (Japan)	1.41 × 1.41	Tatebe et al. (2019)
MPI-ESM1-2-HR	MPI (Germany)	0.94 × 0.94	Mauritsen et al. (2019)
MPI-ESM1-2-LR	MPI (Germany)	1.875 × 1.875	Müller et al. (2018)
MRI-ESM2-0	MRI (Japan)	1.125 × 1.125	Yukimoto et al. (2019)
NorESM2-LM	NCC (Norway)	2.50 × 1.875	Seland et al. (2020)
NorESM2-MM	NCC (Norway)	1.25 × 0.9	Seland et al. (2020)
TaiESM1	AS-RCEC (Taiwan, China)	1.25 × 0.9	Lee et al. (2020)

characteristics defined based on percentile thresholds to analyze the behavior of heatwaves evolution and differences between countries in SEA. We focused on the following questions: (a) How do compound heatwaves change over SEA under different scenarios in the long-term future? (b) How large is the intergenerational difference in exposure to compound heatwaves? (c) What are the dominant roles of exposure changes in different age groups? and (d) How large are regional inequalities with increased population exposure in SEA?

2. Data and Methods

2.1. Datasets

The study used the historical and future daily temperature datasets from 23 CMIP6 ensembles (Table 1; Eyring et al., 2016). The future trajectories in compound heatwaves were projected under three Shared Socioeconomic Pathway (SSP) scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5; O'Neill et al., 2016). We selected the gridded dataset of the observed daily maximum and daily minimum temperature (T_{max} and T_{min}) provided by the Southeast Asian Climate Assessment & Dataset (SACA&D), called SA-OBSv2.0, to evaluate the historical simulations of the model outputs covering the time period 1985–2014. This high-resolution dataset, covering the time period 1981–2017, has undergone accurate quality standard, control to improve its reliability, such as consistent spatial and temporal homogeneity (Van den Besselaar et al., 2017). Because the resolution across the observed dataset and the CMIP6 models varies, we used bilinear interpolation to remap the data with a horizontal resolution of 1.0° for convenience of comparison. The dataset of life expectancy at birth and the annual total population by age group were derived from the United Nations World Population Prospects 2019.

The domain of SEA was defined as (10°S–23°N, 95–140°E) and we mainly concentrated on Indonesia, Malaysia, the Philippines, Singapore, Thailand and Vietnam.

2.2. Definition and Characteristics of Compound Heatwaves

The impact of heatwaves on human health and well-being is a principal global health security topic in the background of the current period of rapid climate change. However, there is no unanimously accepted definition of a heatwave. Two approaches are typically employed to define the prescribed thresholds for heatwaves and the definition of a heatwave varies with the location (Jiang et al., 2019). One approach is centered on the general thermoregulation of the human body, called the absolute threshold, which is measured based on a fixed value. The other one focuses on adaptations to local climatic conditions and taking advantage of a percentile-based (relative) threshold. In view of the climatic conditions and geographical factors in SEA, the latter approach mirrors more accurately the heatwaves in mainland areas and the Maritime Continent (MC) than a fixed value. A compound heatwave event is detected when at least three consecutive days are simultaneously exceeded the 90th percentiles of the daily maximum and minimum temperatures (Y. Chen et al., 2019; Y. Chen & Li, 2017; Oliver et al., 2018). For percentiles estimation, it is based on a 15-day moving window centered on calendar-day corresponding to the reference time period (1981–2010). We calculate it by applying the bootstrap procedure, which could provide the temporally consistent results in reasonable sample sizes (Cowan et al., 2022; Perkins-Kirkpatrick & Gibson, 2017). This procedure divides the 30 years into "base" and "out-of-base" periods and eventually ensures that their estimates are comparable, reducing discontinuity to a great extent (Zhang et al., 2005). The following four heatwave indices are introduced to characterize the heatwave events providing the variates subject to analysis (Della-Marta et al., 2007; Fischer & Schär, 2010; Perkins et al., 2012):

1. Heatwave number (HWN) is defined as the total number of discrete heatwave events per year.
2. Heatwave frequency (HWF) corresponds to the number of participating days in a year involved in heatwave events.
3. Heatwave duration (HWD) is defined as the length (in days) of most sustained yearly heatwave event.
4. Heatwave amplitude (HWA) corresponds to the highest amplitude of the day of the hottest heatwave event.

It is noteworthy that the peak intensity of a heatwave event did not necessarily coincide with the hottest day in a certain year, because the hottest compound heatwave was first calculated from the maximum total amplitude of each discrete heatwave event, then the hottest heatwave day was extracted from this heatwave event.

2.3. Metrics of CMIP6 Model Performance

To evaluate the performance of the compound heatwave characteristics simulated by the CMIP6 outputs in terms of the spatial distribution and interannual variation, we applied four evaluation metrics.

1. The correlation coefficient (COR; Taylor, 2001) is commonly used to quantify similarities among different climate models, with X being the model climatology of a characteristic and Y the corresponding value of the observations. A higher value indicates a higher correlation between the model and observations:

$$\mathrm{COR} = \frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}} \quad (1)$$

2. The ratio of the standard deviation (RSD) is used to recognize information about the differences in amplitude between the models and the observations:

$$\mathrm{RSD} = \frac{\sigma_m}{\sigma_o} \quad (2)$$

   where σ_m and σ_o are the spatial standard deviations of the model runs and the observational data, respectively. A value closer to unity represents a better match of variabilities between the model simulation and the observational dataset.
3. The relative root-mean-square error (RMSE′) is used to quantitatively estimate the empirical reliability and the robustness of the climate simulation capability (Sillmann et al., 2013; Zhu et al., 2020):

$$\mathrm{RMSE}' = \frac{\mathrm{RMSE} - \mathrm{RMSE}_{\mathrm{Median}}}{\mathrm{RMSE}_{\mathrm{Median}}} \quad (3)$$

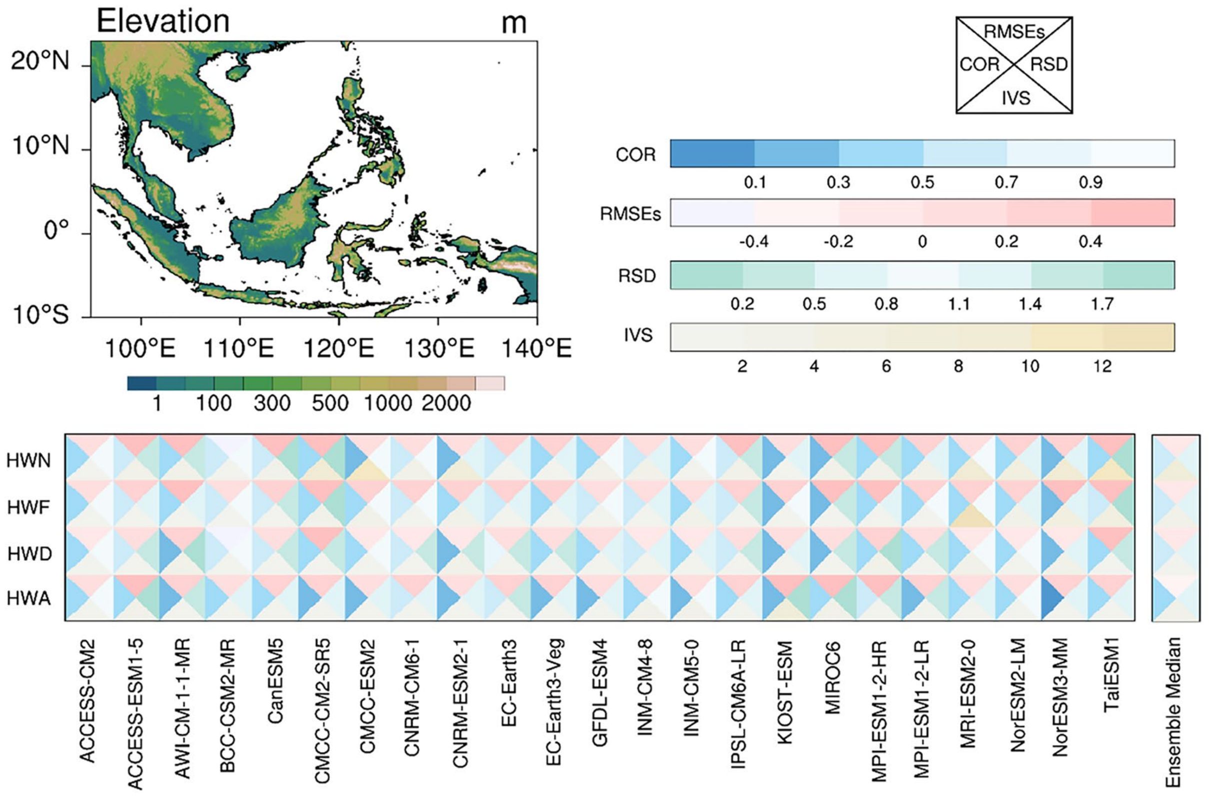

Figure 1. Statistical metrics for the characteristics of heatwaves based on the participating Coupled Model Intercomparison Project Phase 6 ensemble members versus the SA-OBS observations during the time period 1985–2014. COR, correlation coefficient; HWA, heatwave amplitude; HWD, heatwave duration; HWF, heatwave frequency; HWN, heatwave number; IVS, interannual variability skill score; RMSE, relative root-mean-square error; RSD, ratio of the standard deviation.

where $RMSE_{Median}$ being the ensemble median of RMSEs for the existing models. Generally, a negative (positive) RMSE′ denotes that the stimulation performance is superior (inferior) to the majority of the models.

4. The interannual variability skill (IVS) score is applied to evaluate the interannual variability in historical forcings of the CMIP6 outputs relative to the observational dataset and is calculated as:

$$IVS = \left(\frac{SDm}{SDo} - \frac{SDo}{SDm}\right)^2 \tag{4}$$

where SDm and SDo are the interannual standard deviations of the CMIP6 model runs and the observational data, respectively. The IVS is a symmetrical variability statistic used to quantify the interannual variation, with smaller values indicating better agreement with the observations (Gleckler et al., 2008).

Figure 1 shows the statistical metrics for the simulations of compound heatwaves characteristics in the 23 CMIP6 models compared with the reference of the SA-OBSv2.0 observational dataset. There is considerable variation between the models in their simulation of compound heatwaves. Most of the models present a good climate simulation capability, especially BCC-CSM2-MR and EC-Earth3, with correlation coefficients >0.5, IVS <1.3, and RSD mostly close to 1 for all characteristics. However, simulation of TaiESM1 showed a relatively "weak" performance, with positive RMSE′ values for all characteristics. A better model performance is represented by a lighter color. The ensemble median values with light colors are superior to each single model in all respect (Figure 1). This suggests that the results of future projections can be reasonably represented by the ensemble median, which reduces the uncertainties in the participating models to a great extent. We therefore used the ensemble median to represent the projected changes in this study.

2.4. Quantifying Probabilistic Changes to Compound Heat Exposure

Life expectancy at birth in six Southeast Asian countries were employed to estimate the exposure of a person in the 1980s, 1990s, 2000s and 2010s to compound heatwaves across their lifetime (see the **Data Availability**

Statement). According to the life expectancy at different birth years in SEA countries (Figure S1 in Supporting Information S1), compound heatwave events experienced over a lifetime are counted as the sum of the number of compound heatwave events in the corresponding periods. We measured the population exposure in person-days—that is, the number of days per year that exceeded the compound heatwave threshold multiplied by the total population in the age groups exposed. Here, we estimated the change in population exposure following the approach of Jones et al. (2015), which is typically decomposed into three terms:

$$\Delta E = P_1 \times \Delta C + C_1 \times \Delta P + \Delta C \times \Delta P \tag{5}$$

where ΔE is the total change in population exposure, C_1 and P_1 are the number of compound heatwave days and the population at baseline (1985–2014), respectively, and ΔC and ΔP are the changes in the number of compound heatwave days and the population under each scenario relative to the historical period (1985–2014). Hence $P_1 \times \Delta C$, $C_1 \times \Delta P$ and $\Delta C \times \Delta P$ represent the climate component effect, population component effect and their interaction component effect on the changes in exposure.

3. Results

3.1. Future Projections in Compound Heatwaves Under Different Scenarios

3.1.1. Scenario-Medians

Figure 2 shows the projected changes in compound heatwaves at the end of 21st century (2071–2100) relative to 1985–2014 and suggests that the higher emission scenarios would make compound heatwaves more severe and lead to unforeseeable and disastrous consequences on the economy and society. The heatwaves numbers (HWN) over SEA exhibit different magnitudes of increase during 2071–2100 under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios. Under the lower emissions scenarios (the SSP1-2.6 and SSP2-4.5 scenarios), the highest numbers of heatwave events occur in Malaysia, Singapore and Indonesia, while the increase under the SSP5-8.5 scenario is smaller than that under other scenarios as a result of the longer duration of individual heatwave events (Figure 2a). In the mid-term (2041–2070), however, the increase in duration is moderate, the HWN increases consistently with the higher emissions (Figure S2a in Supporting Information S1). In general, compound heatwaves in Indochina Peninsula (ICP) and the MC are expected to intensify under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios relative to historical period. For the characteristics of frequency and duration, compared with the SSP1-2.6 scenario, the compound heatwaves days occur most of the year under higher scenarios (the SSP2-4.5 and SSP5-8.5 scenarios). For example, under the SSP1-2.6 scenario, about 150 heatwave days are observed in the MC, with the most sustained duration of about 11 days. While the SSP5-8.5 scenario shows a very extreme increase, that is, the HWF exceeds 300 days and the HWD also prolongs accordingly to 90 days at the end of the 21st century (Figures 2b and 2c). Phenomenon that was rare in the past may become normal under the high SSP scenario in the future, with a gradually saturated trend in the number of heatwave days in a year. Moreover, similar responses of the HWF and HWD to different scenarios, whether in 2041–2070 or 2071–2100, also shared in the spatial pattern, which may further contribute to the increases in frequency and the total length of compound heatwave events. And for values of increase, the changes in HWF and HWD have the obviously regional differences, with the projected prominent increases in heatwave characteristics in terms of days being more significant in parts of the MC than over the ICP under the same scenario, and this also indicates a slightly lagged response to increased emissions in the ICP.

For the humid, tropical region, the changes of the frequency of extreme heat events are projected to be more pronounced compared with the changes of the amplitude (Cowan et al., 2014; Sherwood & Huber, 2010). Thus, unlike the obviously rising values shown by the HWF and HWD, a weaker trend is seen in the HWA. Notably, the change in HWA shows a different distribution from the HWF and HWD, with a more rapid change in amplitude over the ICP. And regional difference is even more pronounced under high emission scenarios. Inland regions show stronger amplitudes compared to the coastal areas (Figure 2d). This is caused by the variation in the climate and heat content between the MC and the ICP; the large heat content of the surrounding ocean means that the temperature of the MC increases more slowly than the temperature of the ICP (Dong et al., 2021). And the expansion of the urban heat island will lead to the increase of the high temperature extremes over the ICP in the future (Pimonsree et al., 2022; Zhao et al., 2015). Briefly, SEA will experience more frequent, longer-lasting compound heatwaves with higher temperature extremes in the coming decades with increasing emissions scenarios.

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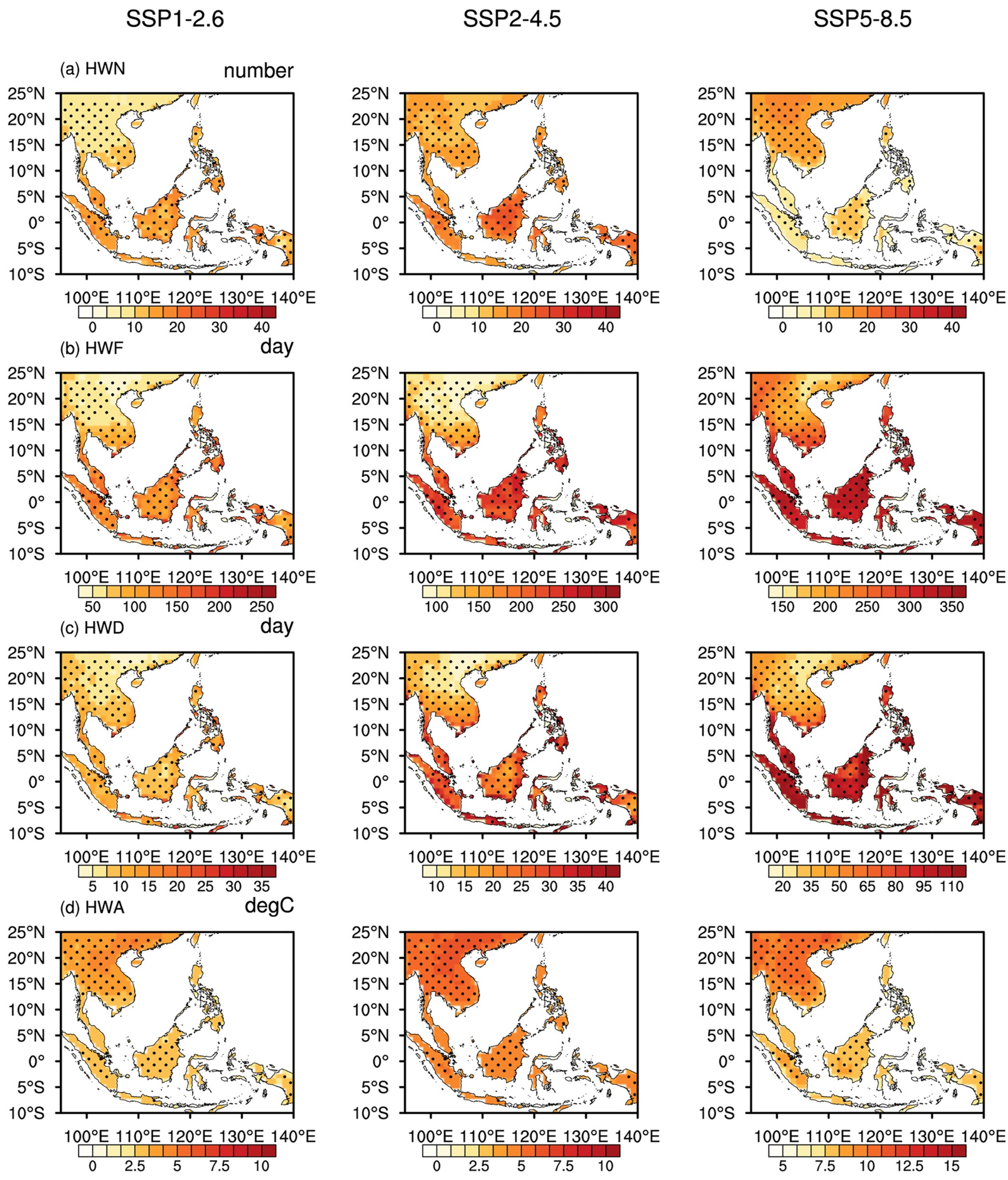

Figure 2. Future changes in the Coupled Model Intercomparison Project Phase 6 ensemble median of heatwave characteristics from 2071 to 2100 under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios relative to 1985–2014. The black dots represent ensemble medians significant at the 95% confidence level. HWN, heatwave number; HWF, heatwave frequency; HWD, heatwave duration; HWA, heatwave amplitude.

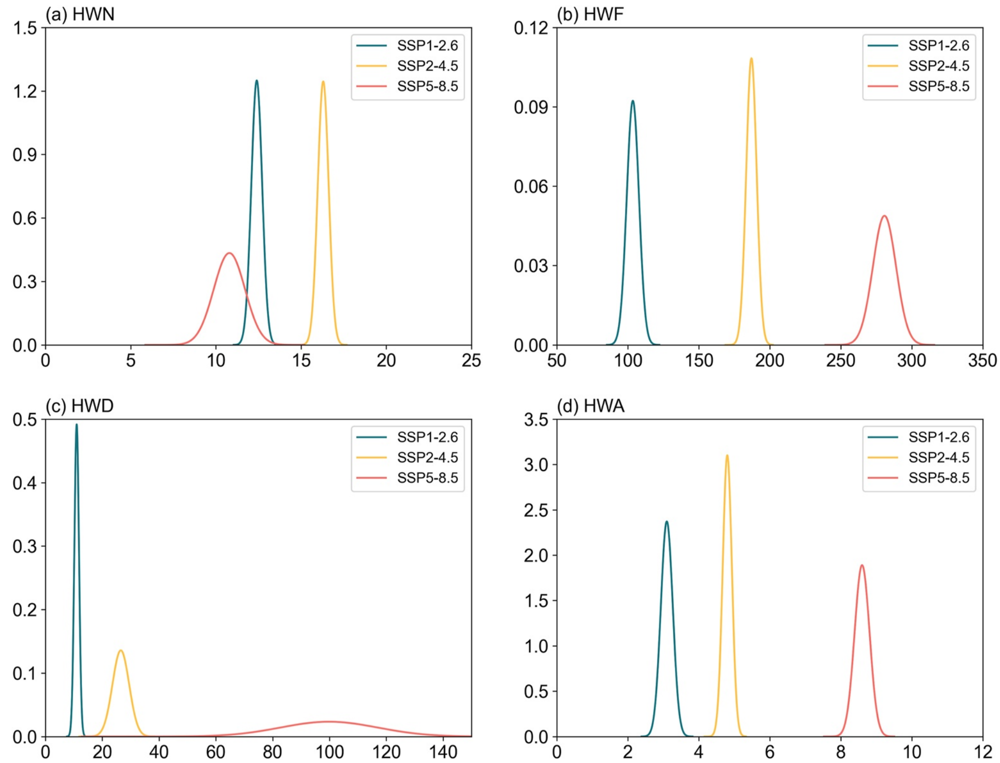

Figure 3. Projected changes in the probability density estimate of heatwave characteristics from 2071 to 2100 under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios relative to 1985–2014. (a) Number of discrete heatwaves in 1 year (units: number); (b) number of heatwave days per year (units: days); (c) length of the longest yearly heatwave event (units: days); and (d) highest amplitude of the hottest yearly heatwave event (units: °C).

3.1.2. Probability Densities

The probability density curves of projected changes in the compound heatwave characteristics under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios relative to 1985–2014 are presented in Figure 3. The probability distribution of the HWF, HWD and HWA shift to the right, indicating an increase in the mean values for each year. The estimated mean values of the HWF increases significantly under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, which are 104, 187, and 281 days, respectively (Figure 3b). The distribution shape of the HWD curve becomes lower and wider as emissions increase, indicating that the range of values is broader and the degree of dispersion also increases under higher scenarios. And the mean values of the HWD are 11, 27, and 100 days under each scenario, respectively, which is also the reason for an abnormal leftward shift in the probability density distribution of the HWN under the SSP5-8.5 scenario (Figure 3c). The mean values of the HWA are 3.1, 4.8, and 8.6°C under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively, with a similar distribution to the HWF (Figure 3d). Thus, except for HWN, the characteristics at the end of the 21st century show that the center of the probability density curves will shift to higher values with increases in GHG trajectories, and the gap between each scenario curve gradually widens (Figure 3). In contrast, the distribution in the mid-term becomes more concentrated, with the curves intersecting at the tails, indicating that these increases remain moderate (Figure S3 in Supporting Information S1). It provides a more intuitive insight into the fact that the future compound heatwaves over SEA will be more extreme from the perspective of multi-dimensional characteristics (Figure 3 and Figure S3 in Supporting Information S1).

3.2. Intergenerational Inequality in Compound Heatwaves

SEA is one of the most vulnerable areas globally to the impacts of climate change and consequent extreme events, such as heatwaves. The region is characterized by coastal areas with large and growing populations and high concentrations of human population density and economically productive. Heatwaves will continue to increase in frequency over the next few decades as global warming progresses. As shown in Figure 4a, the HWN will

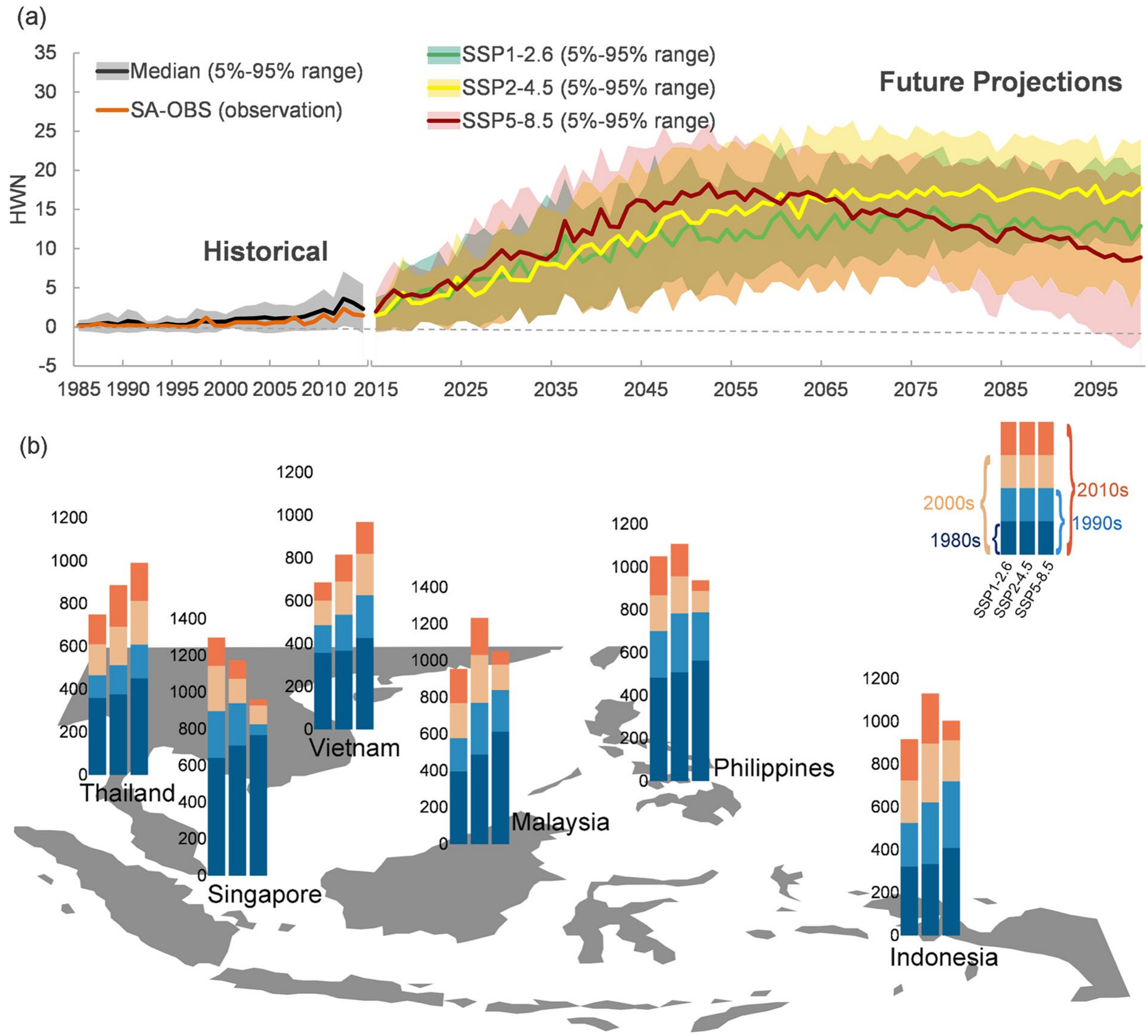

Figure 4. (a) Average annual number of compound heatwaves from 1985 to 2100 over Southeast Asia. The shadows represent 5%–95% uncertainty range. (b) Lifetime heatwave exposure from the 1980s–2010s birth cohorts under the three Shared Socioeconomic Pathway scenarios in selected countries (unit: number).

increase significantly in the near future (before 2050), even if the differences across the scenarios are small. However, after the mid-21st century, the different scenarios show remarkable differences in the magnitude of the changes. Under the sustainable scenario (SSP1-2.6), the HWN over SEA is expected to basically remain at 12–13 by the year 2065 as a result of a reduction in global carbon dioxide emissions according to strict standards, before maintaining a flat trend to an average of 13 in the year 2100. The most significant increase in the HWN from the 2060s occurs under the medium emissions scenario (SSP2-4.5), from about one heatwave in the historical period to 18 by the end of the 21st century. By contrast, the HWN gradually shows a downward trend to 17 in 2055 and is projected to reach about 9 in 2100 under the high emissions scenario (SSP5-8.5). These results indicate that the duration of a single compound heatwave events would get longer, then resulting in fewer identifiable heatwave events.

Figure 4b shows the differences in the number of heatwaves experienced by the birth cohorts in different generations among the countries of SEA. Our results highlight that the lifetime exposure to compound heatwaves increases consistently for the higher emissions scenarios and younger generations. Compared with the cohort born in the 1980s, the younger generations are expected to face more impacts from climate change. For instance, a person born in Indonesia in the 1980s will experience about 320–400 compound heatwaves in their lifetime, while a person born in the 2010s will experience about three times than those of in the 1980s. Under the SSP5-8.5 scenario, people born in the 1990s will experience 312 heatwave events more than people born in the 1980s, whereas those born in the 2010s will experience approximately 600 more heatwaves than those born in the 1980s. Like Indonesia, residents of Singapore, Malaysia and the Philippines, located in the MC, will experience fewer heatwaves under SSP5-8.5 than under SSP2-4.5. Singapore is a highly urbanized island nation in SEA with a tropical climate, where residents are expected to be exposed to more intense and longer-lasting heatwaves. The numbers of compound heatwaves experienced by people over their lifetime are lower under the SSP5-8.5 scenario than under the lower forcing levels, a phenomenon that occurs earlier (from 1900s) relative to other countries. Specifically, under the SSP1-2.6 scenario, the cohort born in the 1980s will, on average, encounter 643 heatwaves, rising significantly to about 1,300 for the cohort born in the 2010s. Under the SSP5-8.5 scenario, the cohort born in the 2010s will experience 197 more compound heatwaves in their lifetime than their parents' generation (born in the 1980s). In Vietnam, the lifetime heatwave exposure is relatively insensitive to the three selected scenarios. A person born in the 2010s who will be exposed to heatwave events appears to become moderate under the sustainable scenario (SSP1-2.6), 690 heatwaves, 800 heatwave events under the SSP2-4.5 scenario and 950 under the SSP5-8.5 scenarios.

Surprisingly, due to the slow increase in HWD over the ICP, the HWN eventually appears to increase with an increase in emissions. By contrast, people in the MC countries will experience fewer heatwaves under the higher emission scenarios. The reason for this result is that the increases in HWD are projected to be more significant over the MC than over the ICP, consistent with Figure 2. A heatwave event over the MC could last up to 30 (94) days under the SSP2-4.5 (SSP5-8.5) scenario, resulting in a decrease in the number of heatwave events detected in a year. Even if this number decreases, this does not mean, that conditions have alleviated in the future (Figure S5 in Supporting Information S1), but rather that the heatwaves experienced by younger generations will be more extreme, and their longer duration will make it difficult to recover, resulting in potential hazards from increased heat-related morbidity and mortality.

3.3. Dynamic Evolution of Relative Importance Among Different Age Groups

Dense populations and the rapid aging of city residents could also further enhance societal vulnerability to compound heatwaves. To discern the relative importance of each effect driving the increased population exposure, we analyzed the contributions of the climatic driver, effect of population changes and the interaction component for different age groups over SEA given the three emissions scenarios at the end of 21st century (Figure 5). In general, the relative importance among climate change, population change, and their interaction effects is varying significantly across groups. Under the SSP1-2.6 scenario, the relative changes in climate, population and the interaction components of the 0–24-year-old population are 126%, −4%, and −22%, respectively. For this group, the negative impact is evident from the population and interaction components, and the increase in population exposure is completely controlled by the climate component. This is mainly due to the young population being expected to shrink by the end of the 21st century (Figure S4 in Supporting Information S1), coupled with the large effects of climate change, offsets the negative growth. The climate component is always larger than the population component, while the 75+ age group under the SSP1-2.6 scenario obviously does not conform to this act. The specific performance is that the role of population growth accounts for 11% of the total effect, slightly higher than the proportion of 6% in the climate effect. In the 25–49-year-old age group, the increased exposure remains largely attributable to climate change at 69%, but the population and interaction effects are 2% and 30%, respectively. In the other words, for the younger population, the increase in population exposure is, to a great extent, linked to the dramatic climate change component at the end of the century.

Interestingly, the population and interaction effects gradually shift to positive with the increasing age of the cohort, while the interaction effect increases significantly and tends to be dominant: the interaction effect accounts for 68%, the climate effect makes a minor contribution of 24%, followed by the population effect at 7% in the 50–74-year-old age group. The proportion of the population effect is greatest among the 75+ age group, accounting for 11%, whereas the climate effect decreases to only 6% (Figure 5; SSP1-2.6). Both the expansion of the population older than 75 years and the deterioration in the living environment would lead to the interaction effect becoming the dominant component. This evolution could also be observed in the mid-term, but the magnitude of each effect is slightly different from that in the end of 21st century. For example, due to the slow rate of decline in the population of the 0–24-year-old group during this period, the interaction effect does not exhibit

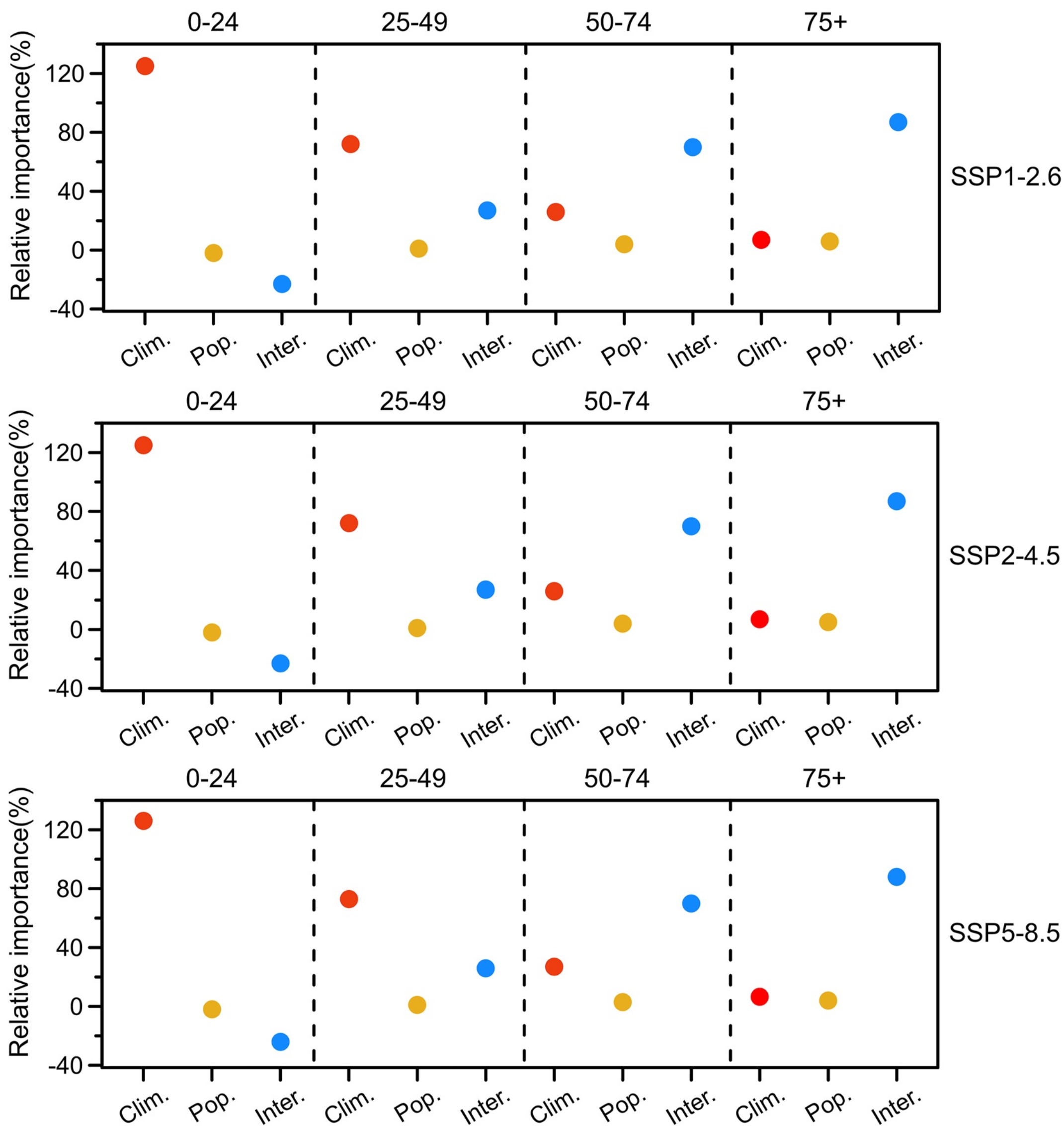

Figure 5. Relative importance of the effects driving increased population exposure across four age groups under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios in 2071–2100 over Southeast Asia. The exposure change contributed by the climate effect is shown in red; the exposure change contributed by the population effect is shown in yellow; and the exposure change contributed by the interaction effect is shown in blue (units: %).

significant negative values under the SSP2-4.5 and SSP5-8.5 scenarios (Figure S6 in Supporting Information S1). The relative changes in these components (including the mid-century and end-century) are largely independent of the emission scenario. A general result is that the interaction effect in population exposure across the age groups is also increasingly important as the forcing radiation. Overall, the frequent occurrence and intensified extremes of compound heatwaves is likely to be caused by the more significant combination of anthropogenic and climatic effects in the future, with severe consequences in SEA.

3.4. Regional Inequalities Related to Increased Population Exposure

At the country-scale, the persistence and growth of regional inequalities in exposure continues to command attention. A comprehensive understanding of future changes in exposure may be crucial in the fight to regional inequalities. We further refined the projected changes in population exposure geographically to various countries in SEA during 2071–2100 (Figure 6). In general, the changes in future exposure exhibit significant increases under all the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios. Indonesia, one of the most populous countries in

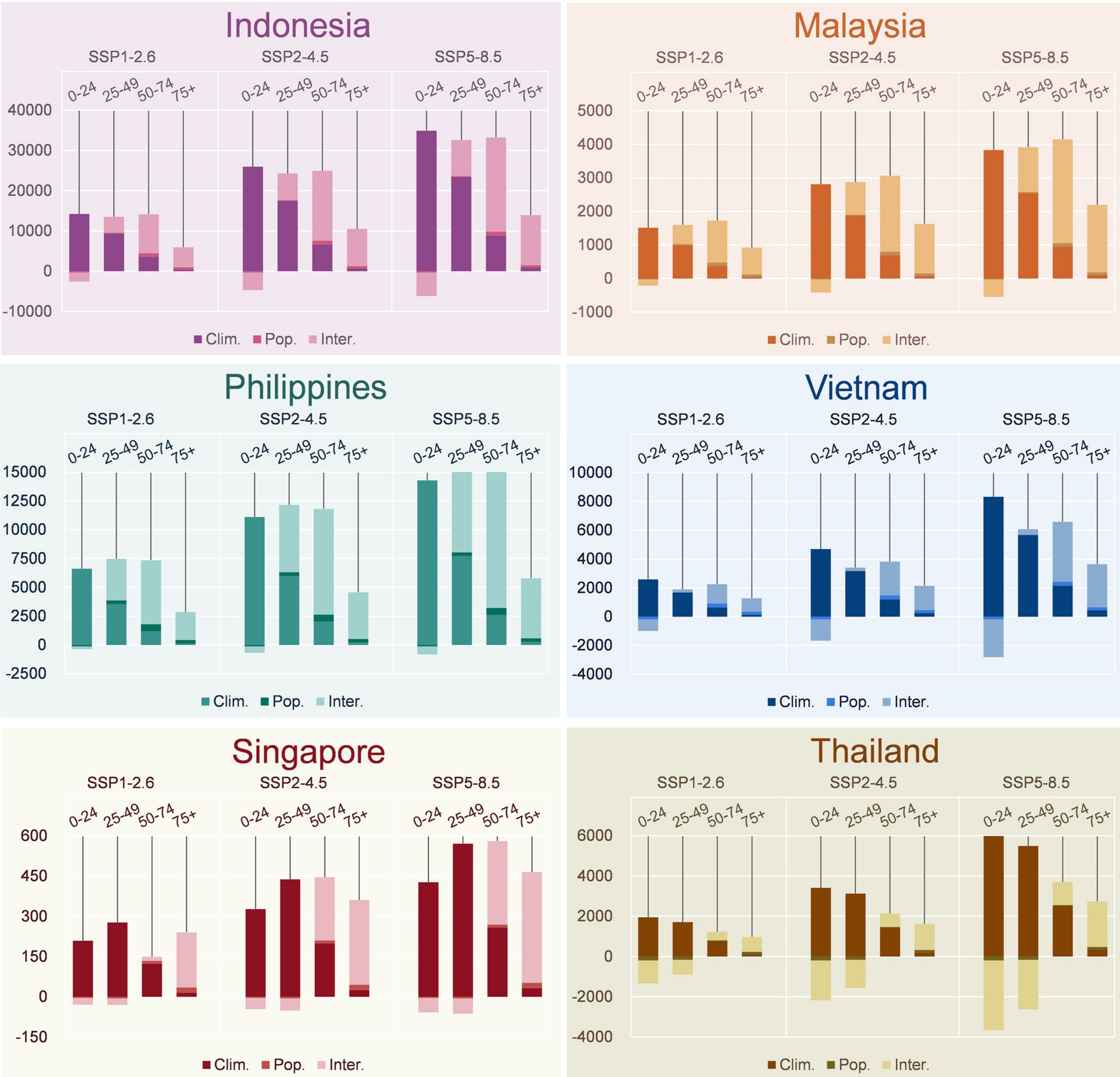

Figure 6. Decomposition of future changes in population exposure across four age groups in Southeast Asian countries during 2071–2100. Different colors in each sub-picture represent exposure changes contributed by climate effect, population effect and interaction effect, respectively (units: person-days, 10^6).

the world, is projected to undertake enormous pressures over an extended time period. Therefore, as an archipelagic country crossing the equator with the largest island area and population, the total change is most striking compared to all other countries in SEA. Among all age groups, the largest net increase in population exposure is expected for people aged 50–74 years, which has gone from 14 billion under the SSP1-2.6 scenario to 25 and 33 billion, respectively, under the higher scenarios. The interaction effect is growing faster in the Philippines than in other countries and is already outpacing the climate effects as the largest driver in the 25–49-year-old cohort. The increase in total exposure of this cohort is about 7.5, 12.2, and 15.6 billion person-days under scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively. However, there is also a substantial contribution from the climate effect, illustrating that, even in the absence of any expansions in population, extreme temperatures alone would amplify the change in exposure. The birth rate and rate of natural change in the Philippines are higher than those of other countries, and they show a relatively flat downward trend (Figures S4b and S4d in Supporting

Information S1). Therefore, the population-related components (population effect and interaction effect) of the 0–24 age group have a positive albeit smaller contribution during 2041–2070, while all other countries have negative growth (Figure S7 in Supporting Information S1). As with the mentioned above, the population effect contributes the least to the total change in exposure across all countries, again emphasizing the relatively minor role that future population changes have in enhancing the rates of future exposure to compound heatwaves.

SEA shows a decline trend in the nascent population at the end of the 21st century (2071–2100). In Singapore and Thailand, both higher- to middle-income countries, the contribution of both population and interaction effects is negative for younger groups, including the 0–24- and 25–50-year-old age groups (Figure 6). Compared with the reference period, 0–24-year-old group shows negative growth with an increasing absolute value. Among the countries of SEA, Thailand and Singapore remain to have the highest proportions of older aged person (United Nations, 2019). By 2021, Thailand has become the third most rapidly aging country in the world, with people aged 60 years and older accounting for 20% of the total population (ERIA and ABCD Centre, 2021; Marks, 2011). Simultaneously, the climate effect still contributes significantly due to the slow growth of the younger population. Likewise, the interaction effect is more pronounced in higher age groups compared to other countries. It is worth noting that the population exposure over the age of 75 years is relatively large in all age groups, especially in Singapore. Lower income countries will be adversely affected by higher exposure to the ongoing threats to the living environment than with higher income countries. It is therefore crucial to have a comprehensive understanding of what is being implemented over SEA to deal with the rapidly aging population and to develop appropriate plannings.

In summarizing, the population of SEA is highly vulnerable to the threats posed by the future compound heatwaves at the end of 21st century. In addition, the increasing role of the combination of climate and population effects in population exposure under the different SSP scenarios highlight the urgency of the mitigation of GHG emissions, proper demographic planning, sustainable development strategies and implementation of regionally dependent adaptation measures to minimize the effects of population exposure to heatwaves.

4. Conclusions and Discussion

Climate change triggers major risks and potential damages to the poverty reduction, steady economic growth, long-term prosperity and the achievement of the Millennium Development Goals over SEA. In particular, the duration and intensity of extremes like heatwaves have imposed severe social and ecological losses in recent decades. If no action is taken to fulfill net-zero emission commitments, heat extremes are projected to become more frequent, intense and of longer duration and will trigger further adverse impacts on both human systems and natural ecosystems. It is crucial for researchers to thoroughly assess the potential risks of compound heatwaves caused by climate change, demographic adjustment and uneven economic development. Based on the SA-OBS observations and CMIP6 models, we investigated the response of compound heatwaves and their corresponding impacts on population exposure in SEA under the sustainable (SSP1-2.6), medium (SSP2-4.5) and high (SSP5-8.5) emissions scenarios against the present day (1985–2014). Our main results are as follows:

1. The projected changes in the characteristics of compound heatwave show distinct increases over SEA, including the HWN, HWF, HWD, and HWA, under all of the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios. All these characteristics track well to increased emissions over recent decades and at the end of the 21st century. Future changes in the HWF, HWD, and HWA are more prominent under the high-emission SSP5-8.5 scenario than under the low- to intermediate-emission scenarios (SSP1-2.6 and SSP2-4.5). The spatial variation of the HWA, which has a moderately increasing trend, is the opposite of that of the HWF and HWD, with a greater growth rate over the ICP than over the MC. The rightward shift in the probability distributions for the various scenarios confirms that increased GHG emissions are associated with a higher HWF, a longer HWD and higher extreme temperatures.
2. In the near-future (before 2050), the HWN increases significantly with increasing emissions, although the differences across scenarios are small. By contrast, after the mid-21st century, the choice of scenario made a remarkable difference in the magnitude of the changes. Under the SSP5-8.5 scenario, the HWN gradually shows a downward trend, even lower than the SSP1-2.6 scenario at the end of the 21st century. A child born in the 2010s will experience two to three times as many compound heatwaves over their lifetime that the age cohorts born in the 1980s. The residents of highly urbanized Singapore would be exposed to more frequent

and more intense with longer duration compound heatwaves. Contemporary younger generations are expected to be confronted to higher risks during their lifetimes compared to their parents' generation.

3. There is a dynamic evolution in relative importance among climate, population and the interaction effects among age groups over the whole SEA region. Climate effects account for the largest proportion of effects for 0–24-year-olds, whereas the population effects and the interaction effects contribute to negative growth. As the number of new births is expected to shrink by the end of the century, the younger cohort will decrease relative to the base period. The interaction effect gradually turns into positive growth with the increase in the cohort age and holds the dominant position under all the scenarios. The climate effect is generally larger than the population effect, although under the SSP1-2.6 scenario, the proportion of the population effect accounts for 11% and the climate effect decreases to 6% in the 75+ age group. The expansion of the elderly population and more extreme climatic conditions combine to make the interaction component essential in driving increased population exposure. The relative changes in the three components are largely independent of the emissions scenarios.
4. Population exposure is projected to increase substantially over SEA in the future. For Singapore and Thailand, two high- to middle-income countries, both the population and interaction effects appear to make negative contributions among people under the age of 50 years. As a result of its large population, Indonesia shows the most dramatic increase in population exposure of all countries. The largest increase is seen in the 50–74-year-old cohort, with the total change in exposure increasing from 14 billion under the SSP1-2.6 scenario to 25 billion and 33 billion under the higher scenarios at the end of the 21st century. Unlike other countries, the proportion of interaction effects in the Philippines rises faster and surpasses the climate effects in the 25–49-year-old cohort. SEA has an aging population, and therefore more efforts to deal with this rapidly aging population and the deteriorating environment would lead to the avoidance of future impacts of climate change.

Some regions where extreme heat is already common may become uninhabitable in the future (Pal & Eltahir, 2016). Characteristics, such as rapid population growth and low adaptability in SEA make the region particularly vulnerable to climate change and consequent heat events. Our work focuses on the four dimensions of compound heatwave characteristics plus emission scenarios plus population level plus country, and results highlight the concerning rate of increase in compound heatwaves during recent decades. It also confirms a sharp increase in future population exposure and leading to the profound topics of the widening of intergenerational difference and regional inequalities. The findings provide additional information by considering day-plus-night compound heatwaves—for example, the variations in the spatial variation of the characteristics of heatwaves, with heatwave days response delayed to increased emission over the ICP than over the MC. Furthermore, it highlights intergenerational differences in the exposure of different birth cohorts to compound heatwaves across SEA. The rapid aging of the population and more extreme living conditions lead to a further increase in the burdens on health (Russo et al., 2019). Therefore, the implementation of heat-related adaptation and mitigation strategies in this region will achieve co-benefits and synergies between reducing threats posed by climate change and devoting the committed dual carbon goals.

Heatwaves may also lead to changes in air quality, which consequently can cause irreversible adverse impacts on human health and other socioeconomic and ecological environments (Fiore et al., 2015; Pyrgou et al., 2018). Specifically, heatwaves and extreme pollution events are both related to a common potential driving mechanism and often occur simultaneously (Ban et al., 2022; Filleul et al., 2006; Jacob & Winner, 2009). In fact, it has been shown that the cascading impacts of heatwaves and pollution events may have a more destructive consequence on social stability and economic crises beyond the sum of their individual impacts (Shen et al., 2016). Future work should consider joint occurrence of heatwaves and pollution such as ozone.

It should be noted that there may still be deviations in this study despite our use of the ensemble median to estimate projected changes. Looking ahead, the "emergent constraint" technique should be adopted in subsequent research to better assess the response of climate models to different emission scenarios. This approach is expected to provide an important way forward and reference for solving the problem of prediction deviations over SEA (Z. Chen et al., 2022; Eyring et al., 2019; Hall et al., 2019).

Higher temperature and more extreme weather exert a major threat to global food supplies. It is prone to collapse for areas with high agricultural productivity and resulting in increased chance of "world food crisis" (Homer-Dixon et al., 2015). Heat-related extreme weather can also create the conditions for new disease outbreaks, coupled with hazards such as air pollution and rising sea levels, which lead to shrinking and deteriorating habitats for humans and animals (Kemp et al., 2022). There is ample evidence that accelerating climate change can cause catastrophic consequences, and understanding catastrophic climate events is also an important point that cannot be neglected for the scientific community.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All the CMIP6 output models are available at https://esgf-node.llnl.gov/search/cmip6/. The SA-OBS datasets are available at http://202.90.199.118/download/grid/download.php. Life expectancy at birth and the annual total population by age group can be obtained from https://population.un.org/wpp/Download/Standard/Mortality/ and https://population.un.org/wpp/Download/Standard/Population/, respectively.

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