Increased population exposure to precipitation extremes under future warmer climates

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Abstract

Precipitation extremes are among the most dangerous climate-related hazards, and these hazards often cause large socioeconomic losses and exert severe human health impacts each year. It is thus crucial to assess future exposure changes to precipitation extremes under different warming scenarios to improve the mitigation of climate change. Here, we project future exposure using a set of Coupled Earth System Model low-warming simulations and RCP8.5 large ensemble simulations. We find that the precipitation extremes are projected to significantly increase over the coming century under different future warming scenarios at both the global and regional levels. Compared to a 1.5°C warmer climate, the 0.5°C of additional warming under a 2.0°C warmer future would increase the number of days of global aggregate precipitation extremes by approximately 3.6% by the end of this century. As a result, the global aggregate exposure is reported to increase by approximately 2.3% if the surface air temperature increases to 2.0°C rather than 1.5°C. An increase in exposure is also obvious for most regions across the world, and the largest increase in the future occurs over North Asia in response to the 0.5°C of additional warming. Furthermore, exposure would increase more rapidly if the temperature increased following the RCP8.5 pathway. The exposure increase varies at the regional level, but in most cases, climate change shows more influential than that of the population; in addition, this influence does not depend on the population outcomes used here.

1. Introduction

Significant increases for climate change risks have been reported around the world due to significantly increasing temperatures, and such temperature increases have already resulted in large losses for society, the economy, and natural ecosystems (Stocker et al 2013, Field et al 2014). The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) has documented that the risks of climate change would be further increased in the future at both the global and regional scale under continuous greenhouse emission scenarios (Stocker et al 2013, Field et al 2014). Faced with these threats of ongoing climate change, the Paris Agreement in 2015 proposed a goal to limit the global warming to no more than 2.0°C and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels (United Nations Framework Convention on Climate Change 2015). However, the warming, even if limited to 1.5°C, would pose serious threats to the populations around the world (King and Karoly 2017, Lehner et al 2017, Jones et al 2018, Lin et al 2018). Thus, voices urging the mitigation of the risks and impacts of climate change have become loud within governmental bodies, scientific communities, and the general public in recent years.

In the context of warming, most of the weather and climate events have become more extreme and...
frequent across the world, which have caused increasing populations to be exposed to hot days, droughts, floods, etc (Easterling et al 2000, Alexander et al 2006, Diffenbaugh et al 2015, Aerenson et al 2018, Gao et al 2018). Precipitation extremes and the related disasters (i.e. flash floods and landslides) are among the most impact-relevant hazards over the world that also have been reported to have increased during the past decades (Westra et al 2013, Donat et al 2016). Notable events include the heavy rainfall that occurred over northern Pakistan during July 2010 that killed approximately 3000 people and affected approximately 20 million people (Lau and Kim 2012) and the severe debris flow induced by the extreme rainfall that occurred in northwest China (Zhouqu) during 2010 that led to thousands of deaths and large economic losses (Wang et al 2016). More recently (June 2013), northern India experienced heavy rainfall that resulted in more than 5000 casualties (Cho et al 2016). The probabilities of such precipitation extremes and related hazards are projected to significantly increase in the next decades as there is a warmer climate across the world (Diffenbaugh et al 2015, Zhou et al 2016, Pfahl et al 2017, Chen and Sun 2018, Chen and Gao 2019, Li et al 2018, Xu et al 2018). Thus, assessments of the impacts from increased precipitation extremes are critical for mitigation and adaptation management.

Exposure, defined as physically being exposed to hazardous conditions, is one of the key determinants of disaster risk (Jones et al 2018). Understanding the impacts of changes in climate extremes to humans is critical to shaping disaster risk and for further effective adaptation. Existing studies have documented that population exposure to dangerous heat temperatures is projected to significantly increase around the world, especially over Africa, South Asia, East Asia, and North America, under the future warming scenarios (Jones et al 2015, Liu et al 2017, Coffel et al 2018, Rohat et al 2019, Zhan et al 2018). Additionally, with the increase of drought occurrence over China, the corresponding exposure presents a remarkable increase in the future even though the population is projected to sharply decrease (Chen et al 2018). Furthermore, if global warming is limited to 1.5 °C versus 2.0 °C, the population exposure to extreme droughts in China is projected to decrease by approximately 17% in response to the 0.5 °C lower warming in the future (Chen and Sun 2019). However, to date, the assessment on the exposure of precipitation extremes in response to warming has received less concern. Based on the newly released stabilized simulations and the RCP8.5 large ensemble simulations from Coupled Earth System Model (CESM), we aim to address the following key issues in this study: (1) to what extent could the exposure to the precipitation extremes across the world be avoided if the global surface air temperature increase is limited to 1.5 °C compared to other temperature increases? and (2) what are the roles of climate and population change on the exposure?

2. Data and methods

2.1. Dataset

The National Center for Atmospheric Research (NCAR) CESM low-warming simulations that were designed for assessments of climate change impacts and mitigation options under the 1.5 °C and 2.0 °C warmer climates, as well as the representative concentration pathways scenario 8.5 (RCP8.5) large ensemble simulations (Kay et al 2015, Sanderson et al 2017), were used here to evaluate the future changes in precipitation extremes and the consequent changes of population exposure around the world. CESM is a fully coupled ocean-atmosphere-land-sea ice model with the horizontal resolution of 0.9° latitude by 1.25° longitude for the atmosphere and land and 1.0° latitude by 1.0° longitude for the ocean. To reach these limited warming goals, a simple Minimal Complexity Earth Simulator model was first employed in the CESM low-warming simulations to produce the optimal emission pathways and then to force the CESM. In these two low-warming emission scenarios, a well-mixed greenhouse gas concentration is redesigned, but other anthropogenic forcing agents, including aerosol, land use, chlorofluorocarbon, and ozone, follow the RCP8.5 protocol (Sanderson et al 2017). These simulations include 11-realization ensembles covering the period of 2006–2100, and the mean annual surface air temperature stabilizes at approximately 1.5 °C (2.0 °C) above preindustrial times at the end of the 21st century (figure S1, available online at stacks.iop.org/ERL/15/034048/mmmedia). In this study, the 1.5 °C and 2.0 °C future climates are thus defined for the period of 2081–2100. Both the historical simulations and the RCP8.5 large ensemble simulations run a 40-realization ensemble of the CESM. The global surface air temperature is projected to increase by approximately 3.7 °C by the end of this century in relative to the preindustrial period under RCP8.5 scenario (figure S1). Here, the first 11 members from these 40 runs were selected for the analyses in order to match the members in the CESM low-warming experiments. The results of the median ensemble means from these 11 members are mainly shown in the following.

To assess the CESM performance, the observed gridded daily precipitation data derived from approximately 16 000 stations and satellite observations, which were acquired from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC), were used in this study. This dataset was constructed using the optimal interpolation approach, and it spanned from 1979 to the present, with a horizontal resolution of 0.5° of longitude-latitude (Chen et al 2008). For the convenience of comparison, the observed dataset was resampled to the CESM grids with a horizontal resolution of 0.9° x 1.25° using a first-order conservative remapping procedure via the Climate Data Operator (CDO). The present day
here is defined as the period of 1986–2005 in both observation and historical simulations of CESM.

The population exposure to precipitation extremes generally means the number of people exposed to the heavy precipitation events, which is defined as the frequency of extremes multiplied by the number of exposed people (Jones et al 2018, Chen and Sun 2019, 2020). The population distribution in the year 2000 and the future projections under different shared socioeconomic pathways (SSPs) from 2010 to 2100 (Jones and O’Neill 2016) were used here to explore the exposure changes from the different future warming climates.

2.2. Bias correction

The precipitation extreme that this study interested in was defined as the daily precipitation greater than or equal to the daily 95th percentile (R95p). The threshold for the 95th percentile was calculated from the past three decades of 1976–2005 for each grid. Assessments of previous studies (e.g. Lin et al 2018) documented that the CESM can reasonably reproduce the probability distributions and time evolution of temperature and precipitation anomalies. Our further show a high capability of the CESM to reasonably capture the spatial pattern of precipitation extreme days based on comparisons to observations (figure S2), with a pattern correlation of 0.8. However, overestimation is clear across the global land areas for the extreme days by the CESM, especially over the regions of Africa, Asia, Australia, and the western coasts of North and South America (figure S2). The quantitative estimation shows approximately 47% overestimation of the extreme days that aggregated over the global land grids. Bias correction is thus urgently needed before further study is implemented.

A popular correction method proposed by Watanabe et al (2012) was employed here that first corrects the statistical parameters for the baseline period and then corrects the projected variables using quantile-based mapping methods. For precipitation, the days of precipitation equal to zero have to be excluded before the estimation of statistical parameters, because the two gamma distributions applied here are only available for positive variables. Thus, a threshold, calculated as the percentile of uncorrected data at which the corresponding observed precipitation exceeds zero, was introduced in this method to treat the portion of uncorrected data less than it as zero. This threshold would be zero when the number of non-precipitation days in the uncorrected data exceeds the observed number of non-precipitation days. Then, the mean (μ) and coefficient of variation (CV) are corrected as follows:

\[
\mu_c = \frac{\mu_p \mu_b}{\mu_b} \quad \text{(1)}
\]

\[
CV = \frac{CV_p CV_b}{CV_b} \quad \text{(2)}
\]

The subscripts o, p, b, and c mean the observation, projection, baseline, and correction. Using the corrected mean and CV, we estimated the two statistical parameters of the gamma distribution, α (shape) and β (scale), which were finally employed to calculate the precipitation via the two-parameter gamma distribution. The parameters of α and β are calculated using the L moments method.

\[
x_c = F^{-1}(F_{x_p} \alpha_p, \beta_p; \alpha_c, \beta_c). \quad \text{(3)}
\]

This correction process was implemented on the daily precipitation for each month. After correction, the overestimation on the precipitation extreme days was substantially reduced across the global lands, especially for some regions of Africa and Asia, when compared with the uncorrected result (figure S2). The pattern correlation of the corrected result was up to 0.94, and the bias decreased to approximately 5% aggregated over the land. Thus, the corrected simulations were used in this study to further assess the changes of precipitation extremes and the associated exposure.

2.3. Estimations of avoided impacts

The avoided impacts due to the lower warming in the future are estimated as follows:

\[
AI = \frac{C_{2.0} - C_{1.5}}{C_{2.0}} \times 100\%. \quad \text{(4)}
\]

Here, AI is the result of the avoided impact, and C1.5 and C2.0 are the changes of precipitation extremes under the 1.5 °C and 2.0 °C warmer climates, respectively, against the present day.

The roles of climate and population changes on exposure were also investigated. As Jones et al (2015) proposed, the exposure change (ΔE) could be decomposed into three parts, including the climate effect, the population effect, and their interaction effect estimated by equation (5).

\[
\Delta E = P_1 \times \Delta C + C_1 \times \Delta P + \Delta P \times \Delta C. \quad \text{(5)}
\]

P1 and C1 are the populations and precipitation extreme days at the baseline time, respectively, and ΔP and ΔC are their corresponding changes at future warmer climates with respect to the baseline time. Thus, the terms of P1 × ΔC, C1 × ΔP, and ΔP × ΔC represents the climate, population, and interaction effect on exposure change. If the equation (5) is divided by E1 for both sides, this equation can provide an estimation of the percentage change for each component (equation (6)). Thus, we can discuss the contribution of each component to the exposure change.

\[
\frac{\Delta E}{E_1} = \frac{\Delta C}{C_1} + \frac{\Delta P}{P_1} + \frac{\Delta C}{C_1} \times \frac{\Delta P}{P_1}. \quad \text{(6)}
\]
3. Results

3.1. Avoided changes of precipitation extremes due to the additional warmings

The future climate simulations of the CMIP5 ensemble documented that the occurrences of precipitation extremes are projected to clearly increase over most regions across the global lands at the end of this century (Sillmann et al. 2013, Chen et al. 2014, Donat et al. 2016). However, how many days of precipitation extremes could be avoided if the surface air temperature increase was limited to 1.5 °C rather than 2.0 °C in the future still remains an open issue. Thus, figure 1 first shows changes in the probability of the occurrence of precipitation extremes (R95p) at the end of the 21st century under different future warmer climates with respect to the present day using the CESM low-warming simulations. The precipitation extremes are projected to increase in the future if the probability rates shown in the panels are larger than 1.0. Our estimation firstly shows that both the mean and coefficient of variation of precipitation are reported to be uniformly increased across the global lands in response to the future warming. Meanwhile, the probabilities of occurrence of precipitation extremes are projected to increase across the world under different future warmer climates, including the 1.5 °C warmer climate, the 2.0 °C warmer climate, and the highest emission scenario (hereafter called ‘RCP8.5 warmer climate’), when compared with that at the present day.

However, after taking a more detailed look at the regional changes of precipitation extremes, a strong regional dependence for the extreme change can be observed across the world, with a relatively larger increase occurring over the Southern Hemisphere while a relatively smaller increase occurs over the mid-high latitudes of the Northern Hemisphere, which is substantially independent of the different future warmer climates. This is especially true for the regions of Africa, in which the occurrences of precipitation extremes show the largest increase in the future. Over the regions of western and eastern Africa, the probability of occurrence of precipitation extremes would be approximately 5 times greater than that in the current climate for both the future 1.5 °C and 2.0 °C warmer climates. Under the RCP8.5 warmer climate, the likelihood of extremes would be 8 times greater over these regions. For Sahara, the regional aggregate occurrence was also projected to increase by at least 3 times under the future warmer climates, despite the probabilities over some parts of this region showing a decrease in response to the warming (figure S3). The warming also yields significant increases of precipitation extremes over some parts of Asia, including East Asia, South Asia, and Southeast Asia, in which the probability increases by approximately 4 times in the future compared to that in the present day. Additionally, the precipitation
extremes over the regions of Central and South America are also projected to show profound increases, with such extremes being approximately 2 times greater in the future than under the current climate. Regions of the mid-high latitudes of the Northern Hemisphere, including North Europe, North Asia, Mediterranean, Alaska, Greenland, and North America, would experience a relatively weak increase of precipitation extremes under the future warmer climates, but with the occurrences at least doubled. Regarding the aggregate average over the global lands, the precipitation extremes would increase by approximately 2 times under the 1.5 °C and 2.0 °C warmer climates and 3 times more under the RCP8.5 warmer climate in the future compared with that at the current level.

Our above assessments show significant increases of precipitation extremes across the global lands in response to the future warmings. However, how many days of precipitation extremes can be avoided if the surface air temperature increase was limited to 1.5 °C rather than 2.0 °C remains an open question to date. Thus, the avoided increases of precipitation extreme days in response to the reduced warming are assessed and displayed in figure S4. In comparison to the 2.0 °C warmer climate, the decrease in warming by 0.5 °C in the 1.5 °C warmer future will help to avoid obvious increases in the number of days of precipitation extremes across the world, especially for the regions of Greenland, western North America, North Asia, and North Europe, in which the number of extreme days can be avoided by at least 5%. Over the regions of Asia (including Central, East, South, and Southeast Asia, as well as Tibet) with highly concentrated populations, the extreme days would be reduced by approximately 3% in response to the 0.5 °C reduced warming. In contrast, the number of extreme days over the regions of the Sahara, the Mediterranean, South Africa, Central America, and the Amazon present a weak decrease in response to the additional 0.5 °C warming in the future. Considering the global lands as whole, the 0.5 °C lower warming in the 1.5 °C warmer future would help to avoid an increase of precipitation extremes by approximately 3.6% when compared to that under the 2.0 °C warmer climate.

If compared to the results with no emission limitations under the RCP8.5 warmer climate, the number of extreme days would be drastically lowered across the global lands when the surface air temperature increase was limited to 1.5 °C (figure S4). The largest avoided increase occurs over the region of Alaska, with a reduction of 44.8% in response to the lower future warming. The smallest avoided increase occurs over the region of Central America (by 18.1%), in which the number of extreme days show a decrease under the 2.0 °C future warming with respect to that under the 1.5 °C future warming. For most of the remaining regions, the lowered warming from the RCP8.5 warmer climate to the 1.5 °C warmer climate can help to avoid an increase of precipitation extremes by approximately 30%. On a global scale, approximately 34.8% of the extreme days can be reduced in response to less warming. Thus, actions of limiting warming are encouraged and urgently needed for the mitigation of climate change.

3.2. Changes in population exposures due to the additional warmings

Risks associated with climate change have been observed to significantly increase in the past decades and would be further exacerbated under the future warming scenarios (Field et al 2014). For example, the increasing heat waves in the future will result in an increase of the aggregate population exposure in African cities by 20–52 times at the end of this century when compared to the current level (Rohat et al 2019). The 0.5 °C additional warming in the 2.0 °C warmer future will lead to approximately 17% more populations exposed to extreme droughts over China in comparison to the 1.5 °C warmer climate (Chen and Sun 2019). In the following, we project future exposure changes to the precipitation extremes throughout the world under different warming scenarios and assess the roles of the warming limitation protocols.

Currently, exposure is the highest over regions of East Asia and South Asia, in which the highest populations live (figure S5). These areas are followed by the regions of the Mediterranean and eastern North America, which have a relatively high population that is also accompanied by a high exposure. Lower exposures can be observed over the mid-high latitudes, including North Asia, Alaska, and Greenland, as well as the desert regions of the Sahara and Australia. With the future warming, the region of Africa, except for the Sahara, exhibits the largest net increase in exposure, followed by the regions of South Asia, the coast of Australia, and North America (figure 2). In contrast, a weak decrease occurs over some parts of Europe and the Sahara. Similar changes are clear for the different future warming scenarios, but with a relatively stronger increase under the RCP8.5 warmer climate and a relatively weaker increase under the 1.5 °C/2.0 °C warmer levels. In comparison to the 1.5 °C warmer future, the 0.5 °C additional warming under the 2.0 °C warmer climate also induces the largest net increase in exposure over most regions of Africa. The other regions, except for the Sahara, the Amazon, and Central America, would also experience a positive response of exposure to the additional warming in the future.

We further compared the exposure changes over rural and urban regions (figure S6). It is clear that the increase of total exposure is mainly contributed by the rapid increase of the exposure over urban regions across the world under future warming scenarios, while exposures over rural regions are projected to decrease or show a weak increase. The drastic increase of exposure over urban regions is closely related to the
rapid urbanization process in the future that does not depend on the SSPs, though the SSP5 used here is the highest urbanization pathway (Jones and O’Neill 2016). The cities located in West and East Africa would suffer from the largest increase of exposure to precipitation extremes in the future; these cities showed an increase of more than 70 times the current level by the end of this century under the 1.5 °C/2.0 °C warmer climate and more than 120 times under the RCP8.5 warmer climate. Consequently, significant increases of total exposure are also projected over these regions, and they are estimated to increase by more than 10 times under the 1.5 °C/2.0 °C warmer climate and more than 20 times under the RCP8.5 warmer climate. In the regions of Asia with highly concentrated populations, especially for East Asia, the urban exposure also shows a rapid increase in the future, with an increase of more than 4 times under the future warmer climates, even though the populations are projected to decrease over this region by the end of this century (figure S5). In most cases, we found the future exposure increase to be predominantly driven by an increase from cities rather than rural regions, in which the exposure is projected to decrease in the future. However, an interesting finding was that the rural exposure over some regions with low concentrations of people, such as Alaska, Greenland, and the Sahara, showed an increase in the future, which is mainly contributed to the increase of precipitation extremes that are further discussed in the next section.

Considering the global land as a whole, the aggregate exposure is estimated to increase by more than 3 times what it is currently by the end of this century under the 1.5 °C/2.0 °C warmer future and more than 4 times under the RCP8.5 warmer climate. This increase is mainly contributed to the increased exposure over urban regions, which showed an increase of 6–10 times under the future warming scenarios, while the exposure over rural regions showed a decrease in the future.

Also noteworthy, the SSP scenarios exhibit less variability in exposure outcomes. Under the future warming scenarios, the total exposure to precipitation extremes presents a profound increase in the future, not depending on the SSPs (figure S7). However, a relatively greater increase can be generally found in the SSP3 scenario (with the high population growth) for most regions of Asia, Africa, and South America, while a relatively greater increase can be found in the SSP5 scenario (with the rapid urbanization process) for the regions of North America and Australia. At the global scale, the exposure also tends to significantly increase for all SSPs under different future warming climates, but with a greater increase occurring in the SSP3 scenario. Thus, the increase of exposure to the precipitation extremes shows much robustness at both the global and regional level.

The exposure increase is obvious in the future worldwide. However, the extent to which the exposure can be avoided if the surface air temperature increase...
is limited to 1.5 °C rather than the other high warming levels is unknown. The avoided exposures are thus calculated from the 2.0 °C and the RCP8.5 warmer climates to the 1.5 °C warmer climate, as shown in figure 3. Clearly, the largest amount of exposure that can be avoided can be seen over North Asia in response to the 0.5 °C lower warming, with a reduction of approximately 6.2%. In most cases, the lowered warming can help people be exposed less to the precipitation extremes in the future. However, there are several regions, including the Sahara, the Amazon, the Mediterranean, South Africa, and Central America, in which the exposure shows a weak decrease in response to the 0.5 °C of additional warming. Additionally, we also evaluated the avoided exposure if limiting the warming to 1.5 °C versus the RCP8.5 warmer climate. The reduction of exposure can be clearly seen across the world. The largest amount of exposure able to be avoided, approximately 55.7%, can be found over the region of Alaska in response to the reduction in warming, while the smallest avoided exposure is shown over the region of East Asia with a value of 10.6%. Our further estimation shows that the global aggregate exposure would profoundly decrease if the temperature increase was limited to 1.5 °C, with the exposure reduced by approximately 2.3% and 30.1% under the 2.0 °C and RCP8.5 warmer climates, respectively. A similar response of exposure to the additional warmings in the future can be found across the SSPs at both the global and regional scale, suggesting a weak role of SSPs on exposure change (figure S8).

3.3. Climate versus population effects

To explore the relative importance of climate and population change, we estimated the change in exposure and its components for different regions under the RCP8.5-SSP5 scenario (figure 4). At the regional scale, climate change appears more influential than the population in driving increased future exposure, as climate change yields a far greater exposure than the population change does for regions across the world, especially for regions located over Asia, Europe, and South America. For example, the increase in exposure to precipitation extremes of approximately 14.5 billion person-days over the Mediterranean region is mainly contributed by climate change, which accounts for an increase of approximately 9.6 billion person-days, while only 2.4 billion person-days and 2.5 billion person-days are contributed from the population and their interaction effects, respectively. In the other words, with the 109% increase of exposure by the end of this century, approximately 72% of the increase is sourced from the effect of climate change. Over East Asia, negative effects are clear from the population and interaction, mainly due to the projected decrease of population in the future over this region. However, climate change exerts a greater effect on exposure that offsets the negative role of the population and ultimately results in the exposure increasing by approximately 101 billion person-days by the end of this century. In contrast, for the regions of Africa, a relatively larger increase can be found from the interaction effect than...
from climate and population changes, suggesting the interaction effect is more significant. Over regions of North America, population change shows a slightly higher role on the exposure increase than the other two components, because SSP5 represents the high population growth scenario over North America (Jones et al. 2018).

Globally, the exposure to precipitation extremes is projected to increase by approximately 1144 billion person-days by the end of this century under the RCP8.5-SSP5 scenario, which is equivalent to an increase of approximately 474% with respect to the current time. This increase is largely contributed by climate change, which can account for approximately 332% of the increase in exposure, followed by the interaction effect that accounts for approximately 120%. In comparison, the population shows a relatively small contribution to the increase of exposure in the future, accounting for approximately 22% of the increase. Briefly, climate change is very likely to lead to increased exposure to precipitation extremes in the future, which is true globally and regionally. Thus, the positive effects of limiting the future warming are clear, and actions to promote such limiting should be encouraged regardless of the political and socioeconomic goals of a country.

4. Conclusion

In this work, we explored alternative spatially explicit projections of future exposure to precipitation extremes at global and regional scales using the CESM simulations. Under the different future warming scenarios (including the 1.5 °C, 2.0 °C, and RCP8.5 warmer climates), we found that the precipitation extreme days are projected to clearly increase by the end of this century across all regions of the world, but with relatively larger increases in the RCP8.5 warmer scenario and relatively smaller increases in the 1.5 °C/2.0 °C warmer climate. For the regions of Africa, the precipitation extreme days showed the largest increase in the future. Especially for the regions of western and eastern Africa, the occurrence probability would be approximately 5 times greater than that of the current time for both the future 1.5 °C and 2.0 °C warmer climates and approximately 8 times greater under the RCP8.5 warmer climate by the end of this century.

Regarding the global aggregate average, the likelihood of precipitation extremes would also increase by approximately 2 times under the 1.5 °C/2.0 °C future warming and approximately 3 times under the RCP8.5 warmer climate.

When we incorporated the projected population change in SSP5, we found that exposure to precipitation extremes showed a profound increase across the global lands, except for some regions of Europe and Asia, in which a weak decrease dominated in the future. Patterns of change were similar across the different future warmer climates, but they were exaggerated under the RCP8.5 future warming scenario. Similarly, the largest net increase of exposure occurs over the regions of Africa, which would show an
increase in exposure of more than 10 times the current level under the 1.5 °C/2.0 °C warmer climates and more than 20 times under the RCP8.5 warmer climate. Globally, the exposure to precipitation extremes is projected to increase by at least 3 times in the future. This significant increase of exposure is mainly contributed by the drastic increase over the cities, due to the rapid urbanization in the future, which is robust at both the global and regional levels.

Limiting warming is quite effective for the precipitation extremes across the world. In comparison to the 2.0 °C warming, the 0.5 °C of less warming under the 1.5 °C warmer climate would help to avoid precipitation extremes by approximately 3.6% by the end of this century. The limiting of warming is especially effective for the regions of Greenland, western North America, North Asia, and North Europe, in which the extreme days can be avoided by at least 5% in response to less warming. As a result, there would be fewer people exposed to the precipitation extreme days in the future. The global aggregate exposure would be profoundly lower by approximately 2.3% if the surface air temperature increase was limited to 1.5 °C rather than 2.0 °C. The largest amount of exposure that could be avoided can be seen over North Asia in response to the 0.5 °C of less warming, with a reduction of approximately 6.2% in the future. If there is no temperature-controlling measure and the temperature was allowed to increase following the RCP8.5 pathway, estimates show that exposure would increase by approximately 30.1% in the future when compared to that under the 1.5 °C warmer climate. A similar response of exposure to the additional warmings in the future can be found across the SSPs at both the global and regional scale.

Finally, we investigated the relative importance of climate and population changes on exposure in the future. We found that both climate and population changes are important drivers of exposure and that climate change shows slightly more influence in driving the increased exposure for most regions across the world. However, the population change presents slightly more influence over the regions of North America because the SSP5 represents a high population growth over this region (Jones and O’Neill 2016). At the global scale, the exposure to precipitation extremes shows a significant increase of approximately 474% with respect to the current time by the end of this century under the RCP8.5-SSP5 scenario, and climate change can account for approximately 332% of this increase. Climate is thus a stronger determinant in driving future exposure to precipitation extremes and that does not depend on the SSPs analyzed here.

One limitation is that the discussion in this study is implemented on the basis of just one model simulation from CESM. The advantage of this study is that the stabilized simulations of 1.5 °C and 2.0 °C warming levels are analyzed here, while the transient warmings are generally analyzed from the CMIP5 simulations, which would be likely to cause large difference between them, especially at regional scales (Chen and Zhou 2016, James et al 2017). Differently, the different composite of radiative forcing in scenarios with stabilized and transient warming would cause different response of the changes in climate variables (precipitation and climate extremes) to the warming that strongly depends on the underlying emission scenarios (Rao et al 2016, Mitchell et al 2017, Xu and Lin 2017). Additionally, the bias-correction process in this study has caused a relatively larger increasing magnitude of precipitation extremes when compared with the results directly estimated from the CESM simulations. That is, the bias correction may be another uncertainty source for the future projection and multiple methods are suggested if the correction implemented for the model simulations. However, the changes in precipitation extremes show quite similar patterns across the global lands with that from the multiple model ensembles of CMIP5 simulations as illustrated by early studies (e.g. Sillmann et al 2013, Chen et al 2014), although there is somewhat difference for the change magnitude. Thus, the changes of precipitation extremes are comparable and robust when compared to the other model simulations. For exposure to precipitation extremes, few studies are visible. We show that the exposure is projected to obviously increase across continent in response to warming in the future, but it is just derived from one model simulation. More works are thus urgently needed in the future for the impact studies or policy decisions basing on CMIP5/6 model simulations.

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Data availability

The data that support the findings of this study are openly available. The CESM simulations can be obtained from the website of http://cesm.ucar.edu/projects/community-projects/LENS/data-sets.html and the observed daily gridded precipitation data can be downloaded at the website of https://climatedataguide.ucar.edu/climate-data/cpc-unified-gauge-based-analysis-global-daily-precipitation.

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References

Aerenson T, Tehbaldi C, Sanderson B and Lamarque J F 2018 Changes in a suite of indicators of extreme temperature and precipitation under 1.5 and 2 degrees of global warming Environ. Res. Lett. 13 035009

Alexander L V et al 2006 Global observed changes in daily climate extremes of temperature and precipitation J. Geophys. Res. 111 D05109

Chen H P and Sun J Q 2018 Projected changes in climate extremes in China in a 1.5 °C warmer world Int. J. Climatol. 38 3607–17

Cheh H P and Sun J Q 2019 Increased population exposure to extreme droughts in China due to 0.5 °C of additional warming Environ. Res. Lett. 14 064011

Chen H P and Sun J Q 2020 Increased population exposure to climate extremes in China under global warming scenarios Atmos. Ocean. Sci. Lett. 13 63–70

Chen H P, Sun J Q and Chen X L 2014 Projections and uncertainty analysis of global precipitation–related extremes using CMIP5 models Int. J. Climatol. 34 2730–48

Chen J, Liu Y, Pan T, Liu Y, Sun F and Ge Q 2018 Population exposure to droughts in China under the 1.5 °C global warming target Earth Syst. Dyn. 9 1097–106

Chen M, Shi W, Xie P, Silva V B S, Kousky V E, Higgins R W and Janowiak J E 2008 Assessing objective techniques for gauge-based analyses of daily precipitation J. Geophys. Res. 113 D04110

Chen N and Gao X J 2019 Climate change in the twenty-first century over China: projections by an RCM and the driving GCM Atmos. Ocean. Sci. Lett. 12 270–7

Chen X and Zhou T 2016 Uncertainty in crossing time of 2 °C warming threshold over China Sci. Bull. 61 1431–9

Cho C, Li R, Wang S Y, Yoon J H and Gillies R W 2016 Anthropogenic footprint of climate change in the June 2013 northern Indian flood Clim. Dyn. 46 797–805

Coffie E D, Horton B M and de Sherbinin A 2018 Temperature and humidity based projections of a rapid rise in global heat stress exposure during the 21st century Environ. Res. Lett. 13 014001

Diffenbaugh N, Swain D L and Tournour D 2015 Anthropogenic warming has increased drought risk in California Proc. Natl Acad. Sci. USA 112 3931–6

Donat M G, Andrew L L, Alexander L V, Paul A and Maher N 2016 More extreme precipitation in the world’s dry and wet regions Nat. Clim. Change 6 508–13

Easterling D R, Evans J L, Groisman P Y, Karl T R, Kunkel K E and Amekne J P 2000 Observed variability and trends in extreme climate events: a brief review Bull. Am. Meteorol. Soc. 81 417–26

Field C B et al 2014 Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects (Cambridge: Cambridge University Press) p 1132

Gao X J, Wu J, Shi Y, Wu J, Han Z Y, Zhang D F, Tong Y, Li R K, Xu Y and Giorgi F 2018 Future changes in thermal comfort conditions over China based on multi- RegCM4 simulations Atmos. Ocean. Sci. Lett. 11 291–9

James R, Washington R, Schleusser C F, Rogelj J and Conway D 2017 Characterizing half—a degree difference: a review of methods for identifying regional climate responses to global warming targets Wiley Interdiscip. Rev. Clim. Change 8 457

Jones B and O’Neill B C 2016 Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways Environ. Res. Lett. 11 084003

Jones B, O’Neill B C, McDaniel L, McCinns S, Mearns L O and Tehbaldi C 2015 Future population exposure to US heat extremes Nat. Clim. Change 5 652–6

Jones B, Tehbaldi C, O’Neill B C, Oleksen K and Gao J 2018 Avoided population exposure to heat–related extremes: demographic change vs climate change Clim. Change 146 423–37

Kay J et al 2015 The community earth system model (CESM1) large ensemble project: a community resource for studying climate change in the presence of internal climate variability Bull. Am. Meteorol. Soc. 96 1333–49

King A D and Karoly D J 2017 Climate extremes in Europe at 1.5 and 2 degrees of global warming Environ. Res. Lett. 12 114031

Lau W K M and Kim K 2012 The 2010 Pakistan flood and Russian heat wave: teleconnection of hydrometeorological extremes J. Hydrometeorol. 13 392–403

Lehner F, Coats S, Stocker T F, Pendergrass A G, Sanderson B M, Raible C C and Smerson J E 2017 Projected drought risk in 1.5 °C and 2.0 °C warmer climates Geophys. Res. Lett. 44 7419–28

Li H X, Chen H P, Wang H J and Yu E T 2018 Future precipitation changes over China under 1.5 °C and 2.0 °C global warming targets by using CORDEX regional climate models Sci. Total Environ. 640–641 543–54

Lin L, Wang Z L, Xu Y Y, Zhang X Y, Zhang H and Dong W J 2018 Additional intensification of seasonal heat and flooding extreme over China in a 2 °C warmer world compared to 1.5 °C Earth’s Future 6 968–78

Liu Z, Anderson B, Yan K, Dong W, Liao H and Shi P 2017 Global and regional changes in exposure to extreme heat and the relative contributions of climate and population change Sci. Rep. 7 43909

Mitchell D T et al 2017 Half a degree additional warming, prognosis and projected impacts (HAPPI: background and experimental design Geosci. Model Dev. 10 571–83

Pfahl S, O’Gorman P A and Fischer E M 2017 Understanding the regional pattern of projected future changes in extreme precipitation Nat. Clim. Change 7 423–8

Rao S et al 2016 Future air pollution in the shared socio–economic pathways Glob. Environ. Change 42 346–58

Rohat G, Flacke J, Dosio A, Dao H and van Marresem M 2019 Projections of human exposure to dangerous heat in African cities under multiple socioeconomic and climate scenarios Earth’s Future 7 528–46

Sanderson B M et al 2017 Community climate simulations to assess avoided impacts in 1.5°C and 2°C futures Earth Syst. Dyn. 8 827–47

Sillmann J, Kharin V V, Zwiers F W, Zhang X and Bronaugh D 2013 Climate extremes indices in the CMIP5 multimodel ensemble: II. Future climate projections J. Geophys. Res. Atmos. 118 2473–93

Stocker T F et al 2013 Climate Change 2013: The Physical Science Basis (Cambridge: Cambridge University Press) p 1535

United Nations Framework Convention on Climate Change 2015 Adoption of the Paris Agreement FCCC/CP/2015/L.9/Rev.1 (Geneva: United Nations Framework Convention on Climate Change)

Wang J, Wang H J and Hong Y 2016 Comparison of satellite–estimated and model–forecasted rainfall data during a deadly debris–flow event in Zhouqu, Northwest China Atmos. Ocean. Sci. Lett. 9 139–45

Watanabe S, Kanae S, Seto S, Yeh P J F, Hiraizumi Y and Oki T 2012 Intercomparison of bias–correction methods for monthly temperature and precipitation simulated by multiple climate models J. Geophys. Res. 117 D23114

Westra S, Alexander L and Zwiers F 2013 Global increasing trends in annual maximum daily precipitation J. Clim. 26 3904–18

Xu Y, Gao X J, Giorgi F, Zhou B T, Shi Y, Wu J and Zhang X Y 2018 Projected changes in temperature and precipitation extremes over China as measured by 50–yr return values and periods based on a CMIP5 ensemble Adv. Atmos. Sci. 35 376–88

Xu Y and Lin I 2017 Pattern scaling based projections for precipitation and potential evapotranspiration: sensitivity to composition of GHGs and aerosols forcing Clim. Change 140 101–13

Zhan M J et al 2018 Changes in extreme maximum temperature events and population exposure in China under global warming scenarios of 1.5 °C and 2.0 °C: analysis using the regional climate model COSMO–CLM J. Meteor. Res. 32 99–112

Zhou B T, Xu Y, Wu J, Dong S Y and Shi Y 2016 Changes in temperature and precipitation extreme indices over China: analysis of a high–resolution grid dataset Int. J. Climatol. 36 1051–66