Increasing impacts from extreme precipitation on population over China with global warming

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Abstract

Precipitation-related extremes are among the most impact-relevant consequences of a warmer climate, particularly for China, a region vulnerable to global warming and with a large population. Understanding the impacts and risks induced by future extreme precipitation changes is critical for mitigation and adaptation planning. Here, extreme precipitation changes under different levels of global warming and their associated impacts on populations in China are investigated using multimodel climate projections from the Coupled Model Intercomparison Project Phase 5 and population projections under Shared Socioeconomic Pathways. Heavy precipitation would intensify with warming across China at a rate of 6.52% (5.22%–8.57%) per degree of global warming. The longest dry spell length would increase (decrease) south (north) of ~34°N. The low warming target of the Paris Agreement could substantially reduce the extreme precipitation related impacts compared to higher warming levels. For the area weighted average changes, the intensification in wet extremes could be reduced by 3.22%, 9.42% and 16.70% over China, and the lengthening of dry spells could be reduced by 0.72%, 4.75% and 5.31% in southeastern China, respectively, if global warming is limited to 1.5°C as compared to 2, 3 and 4°C. The Southeastern China is the hotspot of enhanced impacts due to the dense population. The impacts on populations induced by extreme precipitation changes are dominated by climate change, while future population redistribution plays a minor role.

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1. Introduction

Global-scale warming is unequivocal over the past century and is expected to continue under the continued emissions of greenhouse gases [1]. The warming has exerted adverse impacts on ecosystems, human society, and the economy all over the world, which are mainly related to changes in climate extremes [2]. This is especially the case for China, a region particularly vulnerable to global warming, due to the influences from the East Asian monsoon, complex topography, and the large population [3,4]. The economic losses resulting from disasters related to climate and weather extremes are estimated to be more than 200 billion Yuan per year since 1990, amounting to 2.37% of the gross domestic product in China [5].

Precipitation-related extremes are among the most impact-relevant consequences of a warmer climate. Significant changes in extreme precipitation have been observed at the global and regional scales since the 1950s [6–11]. In China, both the frequency and amounts of heavy precipitation have increased over the majority of the land area in the second half of the past century, although with varying spatial characteristics [12–17]. Additionally, human-induced greenhouse gas emissions have had a detectable effect on the shift from light to heavy precipitation in China [15].

Extreme precipitation is suggested to be further enhanced under continuous warming based on theoretical arguments, i.e., the Clausius-Clapeyron relation in which atmospheric water vapor increases by roughly 7% per degree of global warming [18]. The increase in extreme precipitation is also confirmed in climate model projections, both globally [19–22] and specifically for China [23–28]. In addition, the model projected changes in extreme precipitation are more prominent than the mean precipitation for China, thus exerting greater impacts on natural and human systems [26–28]. There are also seasonal differences in the projected percentage increases in extreme precipitation, related to the differences in seasonal precipitation climatology [27]. Regarding the
uncertainties in the extreme precipitation projections in China, differences in forcing scenarios play a dominant role at the national scale by the end of the 21st century, and the model uncertainty is also important at the regional scale [27].

To reduce further dangerous climate change impact, a total of 175 parties of the United Nations Framework Convention on Climate Change (UNFCCC) have signed the Paris Agreement, which includes a two-headed temperature goal of “holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C” [29]. Significant effort has been devoted to understanding the temperature-related climatic impacts over China, including the uncertainty in the crossing time of warming thresholds [30], changes in temperature and precipitation means and extremes [31–39], and the changes in aircraft takeoff weights associated with a warming climate [40]. Specifically, extreme precipitation is projected to exhibit an overall increase with warming in both frequency and intensity across China [32,34]. However, few studies have paid attention to the associated impacts on populations in China. For heat events, eastern China would experience larger increases in population weighted high temperatures than the East Asian average under global warming, due to the dense population there [38]. For heavy precipitation events, the East Asian monsoon region would experience an increase in population exposure to once-in-20-year events by approximately 30% from 1.5 to 2 °C warming from the multimodel ensemble estimate [41]. Meanwhile, the population exposure to extreme droughts would also increase over China from 1.5 to 2 °C warming [42].

To conclude, our current knowledge is still limited regarding the impacts of extreme precipitation changes on populations under continuous global warming levels for China as well as for its subregions. Moreover, the impacts that could be reduced by achieving the 1.5 °C low warming target compared to higher thresholds (e.g., 2, 3 and 4 °C) deserve further investigation. These issues are of significant value for mitigation and adaptation planning, particularly given the large and uneven distribution of the population in China.

In this study, we aim to address the following questions: (1) how does extreme precipitation change with global warming over China and what are the associated impacts on populations? (2) How much impact is reduced by limiting global warming to 1.5 °C compared to higher thresholds? (3) What are the relative roles of changes in climate and populations on the impacts? Such questions are critical for both policymakers and the public, allowing for the development of comprehensive adaptation strategies.

2. Data and methods

2.1. Data

2.1.1. CMIP5 model simulations

Daily precipitation and monthly near-surface air temperature data from historical simulations and the Representative Concentration Pathways (RCPs) 4.5 and 8.5 projections from 18 climate models that participate in the Coupled Model Intercomparison Project Phase 5 (CMIP5) are used (Table S1 online) [43]. The CMIP5 models, especially the multimodel ensemble median, are generally able to reproduce the observed extreme precipitation at continental and regional scales [27,44–47]. Over China, the CMIP5 models perform better in reproducing the climatological extreme precipitation in eastern China than in western China [46,47]. Moreover, the CMIP5 ensemble median is shown to perform well overall in China and outperforms individual models in reproducing the climatology of extreme indices, and thus is widely used in future projections [27]. The models are selected based on: (1) daily precipitation data availability, and (2) the difference in the timing of the 1.5 and 2 °C warming is no less than 9 years to avoid overlap when 9-year time windows are used to represent respective conditions. For conciseness, we mainly show the results for RCP8.5. Under RCP4.5, only 6 of the 18 models reach a 3 °C warming level, and none reaches a 4 °C warming level by 2100, thus we only show the results of the 1.5 and 2 °C warming for RCP4.5. The results for RCP4.5 generally support those for RCP8.5, and are shown in the Supplementary materials.

2.1.2. Population data

To account for the impacts on the human society, the observed population in 2010 from the 6th national census and projected population for 2011 to 2100 under the Shared Socio-economic Pathways (SSPs) are used [48,49].

2.2. Methods

2.2.1. Extreme precipitation indices

Two extreme precipitation indices, the maximum consecutive 5-day precipitation (RX5day) and maximum consecutive dry days (CDD), defined by the Expert Team on Climate Change Detection and Indices (ETCCDI) are investigated here to represent the wet and dry extremes, respectively [50]. RX5day is a frequently used extreme precipitation index in flood risk assessments [8]. CDD is derived as the maximum number of consecutive days with daily precipitation less than 1 mm, and is often used as one of the meteorological drought or dryness indicators [8,51].

2.2.2. Response of extreme precipitation to global warming

To derive the response of extreme precipitation to global warming, projections of extremes and global mean near-surface air temperature are averaged over decadal periods starting in 2006 and overlapped by 5 years (i.e., 2006–2015, 2011–2020, up to 2091–2100; following Ref. [21]). A linear regression between them is referred to as the response rate, representing mostly the long-term forced signal.

2.2.3. Global warming levels

Extreme precipitation changes at specific warming levels, i.e., 1.5, 2, 3 and 4 °C above the pre-industrial levels (1861–1890), are examined. The warming thresholds are determined using the 9-year running average global mean surface air temperature separately for each model. The specific warming periods are then aggregated over the 9-year windows that are centered on the years when respective warming levels occur. Future changes are compared to the 1986–2005 present-day level.

2.2.4. Probability distributions of land and population

To demonstrate the impact induced by climate change, the probability distributions of land and population are calculated, to illustrate the land area or population affected by certain changes. The extreme precipitation changes at specific warming levels relative to the present-day level are first calculated at each land grid point. The histograms represent the land or population fraction experiencing certain changes. Based on this distribution, we can further identify changes that would occur to a certain proportion (e.g., one-half or one-quarter) of the land area or population.

2.2.5. Population weighted regional average change

To account for how extreme precipitation changes affect population, the population weighted average change (ΔP) is calculated following Eq. (1). The change in climate in each grid point, ΔXp, is weighted by the fraction of people living in that grid, p, and is then summed across the region, spanning latitudes φ1 and φ2,
Fig. 1. Changes in precipitation extremes at targeted global warming levels. (a) Multi-model ensemble median climatology of RX5day over 1986–2005 (unit: mm). (b–e) Multi-model ensemble median responses of RX5day to global warming (b; unit: %/K) and changes from 1.5 to 2, 3 and 4 °C of warming (c–e; unit: % relative to the 1986–2005 present-day level) under the RCP8.5 emission scenario. Stippling denotes areas where at least 2/3 of the models agree on the sign of the change. (f–j) Same as (a–e) but for CDD. Magenta lines in (a) denote the division of the eight subregions—NEC: northeast China; NC: north China; EC: east China; CC: central China; SC: south China; SWC1: southwest China, region 1; SWC2: southwest China, region 2; and NWC: northwest China. The data for Taiwan, Hongkong, Macao, and Hainan Island is missing.
and longitudes $\lambda_1$ and $\lambda_2$. This framework emphasizes changes in densely inhabited regions. It takes into account both changes in climate and population distribution:

$$\Delta \mathbf{X} = \sum_{i=\Phi_1}^{\Phi_2} \sum_{j=\lambda_1}^{\lambda_2} \left( \Delta X_{ij} \times \frac{P_j}{P_{TOT}} \right).$$ (1)

The regional average change using a fixed population in 2010 as weights is regarded as the impact induced by climate change alone, while the change using future population as weights includes contributions from both climate change and population redistribution. The difference between population weighted regional averages under projected population scenarios and that fixed in 2010 is considered as the contribution from population redistribution.

2.2.6. Division of subregions

To examine the spatial differences in impacts, we divide China into eight subregions according to China’s National Assessment Report on Climate Change (Fig. 1a) [52]. This division is based on administrative boundaries as well as on geographical and societal conditions.

2.2.7. Robustness of changes

The robustness of the changes is determined by the model agreement on the signs of changes, as in previous studies (e.g., [21,39]). In this study, robust changes are identified where at least two-thirds of the models agree on the sign of change.

3. Results

3.1. Extreme precipitation induced impacts on population

Climatologically, the magnitudes of heavy precipitation events are largest in southeast China as well as the southeastern Tibetan Plateau, and decrease towards the arid to semi-arid regions in the northwest (Fig. 1a). Correspondingly, the longest dry spell length increases from the southeast towards northwest China (Fig. 1f). The response of extreme precipitation events to future warming is investigated using the projections for 2006–2100.

Fig. 2. Observed population counts and projected population fraction changes under different Shared Socio-economic Pathways (SSPs). (a) Population count in 2010 on a 1°×1° grid basis from the 6th national census (unit: thousand persons). (b–f) Projected changes in population fractions in 2100 under SSPs 1–5 relative to 2010 (unit: 10^−3). The data for Taiwan, Hongkong, Macao, and Hainan Island is missing.
Heavy precipitation events would intensify robustly with continuous warming across China, with a multimodel median area-weighted average response rate of 6.52%/K (5.22%/K–8.57%/K for the interquartile model range), close to that expected from the Clausius-Clapeyron relation (Fig. 1b). Larger percentage increases are projected for western and northern China. The response pattern of extreme precipitation revealed here is generally consistent with that in previous studies also based on CMIP5 multimodels [25,27,28]. The impact of climate change on population also depends on the population distribution (Fig. 2a). It is measured here by multiplying climate change by the population fraction, as was done in previous studies (e.g., [53,54]). The dense population in eastern China enhances the impacts induced by extreme precipitation changes (Figs. 2a and 3a). In contrast, the greater intensification of heavy precipitation in western and northern China has limited impacts on local populations due to the low population density.

The differences between a 1.5 °C and higher warming levels are of specific concern. Global warming increases of 2, 3, and 4 °C would lead to overall intensifications of heavy precipitation compared to a 1.5 °C increase (Fig. 1c–e). However, the changes between the 1.5 and 2 °C warming levels are less spatially consistent, with lower model agreement on the local scale (Fig. 1c). This is probably a result of internal climate variability and model uncertainty, which are important when forced signals are limited for the 0.5 °C additional warming case. Considering the population distribution, the additional influence on the populations in eastern China is the most evident (Fig. 3b–d).

Fig. 3. The impacts of changes in precipitation extremes on populations, calculated by multiplying the changes in precipitation extremes by the population fractions in 2010. (a–d) Multi-model ensemble median responses of RX5day to global warming (a; unit: %/K) and changes from 1.5 to 2, 3, and 4 °C warming (b–d; unit: % relative to the 1986–2005 present-day level) under the RCP8.5 emission scenario multiplied by the population fraction (in % of total population). Stippling denotes where at least 2/3 of the models agree on the sign of the change. (e–h) Same as (a–d) but for CDD. The data for Taiwan, Hongkong, Macao, and Hainan Island is missing.
For extreme dry conditions, in the 21st century, the longest dry spell length is projected to increase south of ~34°N and decrease in the north, with the separation occurring between the Yangtze and Yellow Rivers and featuring a dipolar response pattern (Fig. 1g). This dipolar pattern of change in CDD has also been reported in previous studies [25,27]. The increase and decrease in dry spell length amounts to ~4% per degree of global warming for southern and northern China, respectively. The differences between the 1.5 °C and higher warming levels generally resemble the long-term forced signals, with increased magnitudes and robustness under higher warming levels (Fig. 1h–j). When the population distribution is taken into account, the lengthening of dry spells would exert a greater impact in southern China (Fig. 3e–h).

As noted above, changes in extreme precipitation at the local and regional scales tend to be obscured by noise, particularly for the low signal-to-noise ratio case of the difference between the 1.5 and 2 °C warming levels (Fig. 1c, h). To illustrate this effect, we employ the probability distributions of land and population, by calculating the fractions of land areas or populations experiencing certain changes. This spatial probability perspective demonstrates robust signals of change over the entire region, and is more informative than the simple regional mean.

We investigate the probability distributions for changes in the wet and dry extremes, under global warming levels of 1.5, 2, 3 and 4 °C. For heavy precipitation events, there is high agreement among models that the distribution would shift towards wetter conditions meanwhile stretch in the upper tail (Fig. 4a, b). Thus more intense heavy precipitation events would occur across larger areas and affect a larger fraction of the population over China as the climate warms. In addition, there would be an emergence of extremes outside the historical ranges, as indicated by the extension of the upper tail of the distribution.

According to the multimodel median estimates, the area weighted average increases in heavy precipitation intensity over the whole China are 4.64%, 7.84%, 14.49% and 21.36% over the 1986–2005 present-day level, for global warming levels of 1.5, 2, 3 and 4 °C, respectively (Fig. 4a). Specifically, one-quarter of the entire land area would experience an intensification of more than 12.00%, 15.22%, 21.58%, and 31.53% at global warming levels of 1.5, 2, 3 and 4 °C, respectively. Given the population distribution in 2010, one-quarter of the population would experience an intensification of 12.19%, 15.38%, 21.76%, and 29.02%, correspondingly (Fig. 4b). Using future population projections under different SSPs yields similar results (Fig. S1 online).

For the longest dry spell length, no consistent shift in its distribution is expected, because of opposing changes in northern and southern China (Fig. 4c, d). However, the stretching of the distribution on both sides with increasing warming levels indicates increases in occurrences of both longer and shorter consecutive dry spells (Fig. 4c). In particular, the stretch in the upper tail of the distribution corresponds to a larger area being affected by very long dry spells in southern China, while the stretch in the lower tail reflects the decreases in CDD in northern China. When the population distribution is taken into account, the dense population in southern China where longer CDD is projected highlights the changes in the upper tail of the distribution (Fig. 4d). In contrast, the shortened dry spell length in western and northern China has little influence on population due to the low population density there, as shown by the slight changes in the lower tail of the population weighted distributions (Fig. 4d). As a consequence, the population weighted average change that emphasizes the increase in CDD in southern China is larger than the land area weighted change (Fig. 4c, d). If the population distribution was kept at the 2010 level, a 25% (10%) share of the population would suffer from an extension of dry spells by more than 8.51% (14.65%), 10.38% (17.72%), 11.34% (19.35%) and 13.70% (21.51%) at global warming levels of 1.5, 2, 3 and 4 °C, respectively.

Fig. 4. Probability distributions of land and population. Distributions of the land fraction (a, c) and population (b, d) experiencing certain changes in RX5day (a, b) and CDD (c, d) aggregated over China at global warming levels of 1.5, 2, 3 and 4 °C under RCP8.5 (units: %). Changes in precipitation extremes are given as percentages relative to the 1986–2005 present-day climatology. The observed population in 2010 is used to calculate the distributions in (b, d). Solid lines denote the multimodel ensemble medians and shadings denote the interquartile model ranges. The box-whisker plots denote multimodel median changes to the 10th, 25th, 50th, 75th, and 90th percentiles of land area or population, and the dots denote the land area or population weighted average changes.
3.2. Reduced impacts by the 1.5 °C low warming target compared to higher thresholds

Then how much of the impact can be reduced by the 1.5 °C low warming target compared to the higher thresholds of 2, 3 and 4 °C? It is measured by the area or population weighted mean of the additional changes induced by additional warming. The reduced impacts over the entire China and its subregions are examined. If warming is limited to 1.5 °C, greater impacts could be reduced when compared to higher global warming levels (Fig. 5). For heavy precipitation, the reduced impacts differ only slightly from region to region. The area weighted intensification in RX5day can be reduced by 3.22%, 9.42% and 16.70% for a warming of 1.5 °C compared to 2, 3 and 4 °C, respectively, over the entire China over the present-day level, according to the multimodel median estimates (Fig. 5a). When the population distribution is taken into account, central, east and south China would experience the largest impacts from heavy precipitation induced by additional warming (Fig. 5b). The high model consistency in the reduced impacts confirms the robustness of the results. Even for the differences between the 1.5 and 2 °C warming thresholds, significantly reduced impacts are expected over most of the subregions (Fig. 5a, b).

For the dry extremes, the impacts from additional warming differ in sign for the southern and northern parts of China (Fig. 5c, d). Further warming above 1.5 °C would induce the largest impacts from longer dry spells for central, east, southwest and south China. The lengthening of dry spells in the southeastern China would be reduced by 0.72%, 4.75% and 5.31% for the 1.5 °C warming

![Fig. 5](image-url) Reduced impacts by limiting global warming to 1.5 °C compared to 2, 3 and 4 °C derived from RCP8.5 projections. (a) Additional area weighted average changes in RX5day from global warming of 1.5 to 2, 3 and 4 °C over China (CHN) and its eight subregions derived from multimodel median (unit: % relative to 1986–2005). (b) Same as (a) but for the population weighted regional average changes in RX5day. The population distribution in 2010 is used as the weight and is given in %. (c), (d) Same as (a), (b) but for CDD. Stars indicate where at least 2/3 of the models agree on the sign of the change.
compared to 2, 3 and 4 °C, respectively, as estimated from the multimodel medians (Fig. 5c). We note that the model consistency in the reduced impacts for the dry extremes is lower than that for the heavy precipitation events. In particular, the reduced impacts between the 1.5 and 2 °C warming are insignificant for the majority of the subregions (Fig. 5c, d). This is possibly because of the weaker coupling of dry extremes with temperature than for heavy precipitation. The large uncertainty in the projections of droughts and dryness has been widely acknowledged (e.g., [8,51]).

To conclude, a robust decrease in the impacts from heavy precipitation is expected over the entire China if global warming is limited to 1.5 °C compared to higher levels. Meanwhile, reduced impacts from dry extremes are projected for the southeastern part of China. Therefore, it is worth noting that the southeastern part of China is the hotspot that is impacted greatly by additional warming from both wet and dry extremes.

3.3. Roles of climate change and population redistribution in impacts

As illustrated in Eq. (1), the impact of climate change on population is determined by changes in both climate and population distributions. To account for the relative contributions from the two components, we estimate the impacts induced by future population redistributions, derived as the differences in population weighted average changes between projected population scenarios and that observed in 2010.

The absolute population is projected to decrease by the end of 21st century under the socio-economic development pathways of SSP1 (Sustainability), SSP2 (Middle of the road), SSP4 (Inequality), and SSP5 (Fossil-fueled development), except for SSP3 (Regional rivalry) (Fig. S1 online). Specifically, substantial decreases in population are projected for large parts of eastern China except for SSP3, while increases are projected in southern China in all cases. The population fractions are considered to be important and are used as weights for the regional average changes. The population fraction would increase in the coastal areas of southeastern China and northwestern China while it would decrease in most part of eastern China (Fig. 2b–f). This indicates a redistribution of the population fraction from eastern China mainly to southeastern China.

For heavy precipitation events, the influence of future population redistributions on the total population weighted average changes is weak and uncertain across models (Fig. 6a). This is probably because of the small spatial difference in extreme precipitation changes (Fig. 1b). Therefore, climate change plays a dominant role in the overall impacts of heavy precipitation events on population, while the role of population redistribution is negligible and insignificant.

For dry spell lengths, however, future population redistributions tend to further enhance the impacts on populations, leading to additional increases in the population weighted average changes in CDD (see dotted bars in Fig. 6b). This is linked to an increase in the population fraction in the coastal areas of southeastern China where CDD also increases, and a decrease in the population fraction in the north where CDD decreases as well (Figs. 1g and 2b–f). In other words, the future population redistributions emphasize the projected lengthening of dry spells in the coastal areas of southeastern China in the population weighted regional mean. The relative contributions from population redistributions to the overall impacts depend on population projections, but significant positive contributions are projected overall (Fig. 6b). A maximum contribution of approximately 11% (~5%–42% for the interquartile model ranges) is found under SSP3. Hence, for the dry extremes, climate change dominates over population redistribution in the impacts on populations, with the latter playing a small but significant role.

We confirmed the results using the RCP4.5 emission scenario. The response patterns and overall changes in precipitation extremes are similar between the different emission scenarios (Figs. S3–S8 online), except that the projected lengthening of CDD in southern China is weaker under RCP4.5 than under RCP8.5 (cf. Figs. 1g and S3c online). In terms of the reduced impact

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**Fig. 6.** Contributions of future population redistributions to impacts. Population weighted average changes in RX5day (a) and CDD (b) over China at global warming levels of 1.5, 2, 3 and 4 °C derived from RCP8.5 projections (unit: % relative to the 1986–2005 present-day period). Solid bars denote the population weighted regional average changes using population projections in 2100 from SSPs 1–5 as weights. Dotted bars denote the regional average changes induced by population redistributions, determined as the differences in the population weighted average changes between projected population scenarios and POPU2010. The bars denote multimodel medians, and the vertical lines indicate interquartile model ranges. Stars indicate where at least 2/3 of the models agree on the sign of the change.
of the 1.5 °C warming threshold compared to 2 °C, both emission scenarios indicate robustly reduced impacts from heavy precipitation events, but indicate insignificant differences from dry extremes (cf. Figs. 5 and S7 online). Quantitatively, the reduced intensification of RX5day is 3.22% (2.24%–5.14%) under RCP8.5 and 3.95% (2.50%–6.14%) under RCP4.5 for China overall. For the relative importance of climate change and population redistribution in impacts, it is consistently shown that population redistribution plays a negligible role for the wet extremes, while increases in the impacts induced by the dry extremes with high model consistency, although the magnitude is small (cf. Figs. 6 and S8 online). The consistency between different emission scenarios enhances the robustness of the results.

4. Conclusions

Extreme precipitation events, including both floods and droughts, have caused substantial social and economic losses in the past. As the climate warms, extreme precipitation events are expected to change more noticeably than the mean precipitation, and exert further impacts on populations and society. It is of crucial importance to investigate the impacts of extreme precipitation changes on populations, particularly in China, which is one of the most densely inhabited countries in the world and has long been overwhelmed by precipitation extremes. In this study, the responses of both wet and dry extremes to global warming as well as their corresponding impacts on populations are studied by employing climate and socio-economic projections. The potentially reduced impacts by limiting global warming to 1.5 °C compared to higher thresholds are investigated. Furthermore, the relative roles of changes in climate and populations in the impacts are compared. The major findings are summarized below.

(1) As the climate warms, heavy precipitation events (RX5day) are projected to intensify by 6.52% (5.22%–8.57%) per degree of global warming averaged in China. The impacts on populations are the greatest in eastern China due to the dense population. The response of the longest dry spell length to warming features a dipolar pattern, with an increase south of ~34°N and a decrease in the north. The lengthening of dry spells exerts a greater impact on the populations in southeastern China because of the dense population.

(2) At global warming levels of 1.5, 2, 3 and 4 °C above the pre-industrial level, one-quarter of the population would experience an intensification in heavy precipitation events of more than 12.19%, 15.38%, 21.76%, and 29.02% over the present-day level, respectively. The corresponding changes are 8.51%, 10.38%, 11.34%, and 13.70%, respectively, for the extension of dry spells.

(3) The reduced impacts from heavy precipitation are robust across China. If global warming is limited to 1.5 °C compared to the higher levels of 2, 3 and 4 °C, the intensification in RX5day can be reduced by 3.22%, 9.42% and 16.70% of the present-day level for China overall, respectively. Meanwhile, the lengthening of dry spells can be reduced in southeastern China by 0.72%, 4.75% and 5.31%, respectively. Therefore, southeastern China is the hotspot that would be relieved substantially by the 1.5 °C low warming threshold from both wet and dry extremes compared to higher warming levels.

(4) The impacts on populations induced by extreme precipitation changes are dominated by climate change, while population redistributions play a minor role. For heavy precipitation events, the influence of future population redistributions on the overall impacts is negligible. For dry spell lengths, future population redistribution further enhances the impacts on populations with high model consistency, with a maximum contribution of approximately 11% (~5%–42%) to the total changes under the pathway of regional rivalry (SSP3).

Limiting global warming to 1.5 °C compared to the higher thresholds would lead to substantially reduced impacts from both the wet and dry extremes for China, thus highlighting the significance of the Paris Agreement low warming target and efforts for mitigation. The reduced impacts are independent of the emission scenarios considered, as supported by the results from climate projections under RCP4.5 (see Supplementary materials online). Our research is one of the first studies to focus on the impacts on populations caused by future extreme precipitation changes over China. The uneven population distribution, particularly the dense population in southeastern China, has significant consequences for the impacts. The enhanced impacts from both intensified heavy precipitation and lengthened dry spells in southeastern China due to the dense population pose high risks of both floods and droughts, thus requiring efficient and timely regional adaptation activities.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Wenxia Zhang designed the research, performed the analysis, and revised the manuscript. Tianjun Zhou designed the research, provided comments and revised the manuscript.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2019.12.002.

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