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Increased population exposure to extreme droughts in China due to 0.5 °C of additional warming

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Abstract

Drought, one of the major natural disasters in China, generally causes the largest socioeconomic loss each year and also has severe human health impacts. It is thus crucial to assess the changes in droughts in this region under different climate change scenarios. This study examines the impacts of stabilized 1.5 °C and 2.0 °C warming at the end of the 21st century on drought events in China by using a set of coupled Earth system model low-warming simulations. If warming is limited to 1.5 °C or 2.0 °C, these simulations suggest that droughts will become more frequent and more intense compared to the present day, particularly over the northern regions of China. In comparison to the 1.5 °C warmer future, the 0.5 °C additional warming in the 2.0 °C warmer future will account for approximately 9% of the increase in the drought occurrence in China and approximately 8% of extreme droughts, while there are relatively small responses for moderate and severe droughts. Consequently, the additional warming would lead to significantly higher drought impacts, and the population exposure to the extreme droughts is projected to increase by approximately 17%, although the exposure to moderate droughts decreases. Therefore, our results suggest that the mitigation of anthropogenic warming by 0.5 °C to achieve the 1.5 °C warmer climate instead of the 2.0 °C climate may have benefits for future drought risks and impacts.

1. Introduction

The goals of the 2015 Paris Agreement were a commitment to limiting the global warming to no more than 2 °C and the pursuit of efforts to limit the global mean surface temperature (GMST) increase to 1.5 °C above preindustrial levels (United Nations Framework Convention on Climate Change 2015); this agreement brought international action against climate change to a new stage. The strong efforts from governments to combat climate changes are encouraging to the public. Since GMST has already increased by 0.9 °C, a limited increase in temperature (~0.6 °C) will reach the 1.5 °C limit (Stocker et al 2013). Thus, performing comprehensive assessments on climate changes and providing reliable information for policymaking with respect to climate mitigation and adaptation are urgently needed.

In recent years, there have been increasing efforts devoted to the investigation of the extreme climate changes around the world at the 1.5 °C and 2.0 °C warming levels (e.g. Chen and Sun 2015a, Huang et al 2016, Jiang et al 2016, Ahmadalipour et al 2017, Donnelly et al 2017, King et al 2017, Raftery et al 2017, Schurer et al 2017, Paltan et al 2018, Sui et al 2018, Zhang et al 2018). For example, Huang et al (2017) assessed the impacts of 1.5 °C and 2.0 °C warming on the environmental changes over the global drylands, and the results showed that the people in these regions would suffer from decreased maize yields, increased long-lasting drought, and more favorable conditions for malaria transmission if the global rise in temperature increases from 1.5 °C to 2.0 °C. Karmalkar and Bradley (2017) evaluated the effects of different levels of warming on temperature and precipitation changes.
across the contiguous United States. Similarly, Chen and Sun (2018) evaluated the responses of the large-scale extreme climate changes from the additional 0.5 °C warming across China.

Most previous studies utilized the model outputs from the Coupled Model Intercomparison Program phase 5 (CMIP5) for periods in which the increase in GMST reaches 1.5 °C and 2.0 °C during the 21st century under Representative Concentration Pathway (RCP) scenarios. The substantial disadvantage of this approach is that the increases in GMST to 1.5 °C and 2.0 °C are only present transiently in the CMIP5 simulations, which is likely to account for the large difference in the results compared with models using the stabilized warming levels (James et al 2017, Lehner et al 2017, Lin et al 2018). Recently, the National Center for Atmospheric Research (NCAR) released a set of climate simulations specifically targeting the stabilized warming levels of 1.5 °C and 2.0 °C in the late 21st century using the Community Earth System Model (CESM; Sanderson et al 2017). This dataset has been widely used to assess the impacts of different levels of warming on climate change across the world (e.g. Lehner et al 2017, Aerenson et al 2018) as well as in China (e.g. Li et al 2018, Lin et al 2018).

Drought, one of the most devastating natural disasters in China, was reported to become more frequent with longer durations and larger extents than in the past decades (Chen and Sun 2015b, Zhai et al 2017). The economic losses caused by droughts accounted for approximately 19% of the losses from all meteorological disasters from 1985 to 2014 (China Meteorological Administration (CMA) 2015). With the increasing warming in the future, the dry conditions across China will be further aggravated, and their potential impacts on the social-economic development will also be amplified (Sun et al 2017, Chen and Sun 2018, Liang et al 2018).

However, to date, the assessment on drought changes in response to the additional 0.5 °C warming in China has received less attention. Based on the newly released stabilized simulations from CESM1, we aim to address the following questions in this study: (1) to what extent could the occurring risks of droughts be avoided if the global warming was limited from 2.0 °C to 1.5 °C? And (2) how will the population exposure to droughts differ in a 1.5 °C warmer climate compared with a 2.0 °C warmer climate?

2. Data and methods

2.1. Model dataset

CESM is a fully coupled ocean-atmosphere-land-sea ice model with a horizontal resolution of 0.9° latitude and 1.25° longitude for the atmosphere and land. The low-warming simulations by CESM1 are designed for the assessments of the climate change impacts and mitigation options under the 1.5 °C and 2.0 °C warming world (Kay et al 2015, Sanderson et al 2017). A simple Minimal Complexity Earth Simulator model was first used to determine the optimal emission pathways leading CESM1 to achieve the long-term 1.5 °C and 2.0 °C global warming. In the 1.5 °C and 2.0 °C emission scenarios, non-greenhouse-gas concentrations, including aerosol emissions, land use, ozone, and CFCs follow the RCP8.5 scenario throughout the simulations. The emission pathways are then applied to force the CESM1, and a set of 11 ensemble simulations are produced that stabilized warming at 1.5 °C and 2.0 °C by the end of the 21st century. For more details on the emission pathways and simulations, please refer to Sanderson et al (2017). In this study, all 11 ensemble members are used to quantify the uncertainties from internal climate variability. The 1.5 °C and 2.0 °C future climates are defined for the period from 2081 to 2100 that reaching to the targeting stabilized warming levels (Sanderson et al 2017), and the present-day is taken as the period from 1986 to 2005.

The observed monthly gridded datasets (0.5° × 0.5°) used for the validation of the model performance in this study are acquired from the Climate Research Unit (CRU; Harris et al 2014). The precipitation is generally underestimated from the CRU dataset, but it can capture the drought change well (Hu et al 2018), which is the main topic in this study. For the convenience of comparison, the CRU datasets are resampled to the CESM grids with a horizontal resolution of 0.9° × 1.25° using a first-order conservative remapping procedure via the Climate Data Operator (CDO).

2.2. Bias correction

Previous studies (Lin et al 2015, Li et al 2016) have indicated that the CESM1 is able to simulate the present-day climate in China reasonably well. For example, the model can reasonably capture the probability distributions and time evolution of temperature and precipitation anomalies across China (Lin et al 2018), as well as the variability of aridity (Lin et al 2015). However, our analyses show that large biases still remain in the temperature and precipitation across China (figure S1 is available online: stacks.iop.org/ERL/14/064011/mmedia), which is in line with the findings by Lin et al (2018). Therefore, bias correction is urgently needed before further study is implemented. A bias correction method proposed by Watanabe et al (2012) is applied to the CESM1 simulations. The substantial advantage of this method is that it enables the time changes of basic statistics to be nearly identical between the uncorrected and bias-corrected data (Watanabe et al 2012).

Compared with other correction methods, in which the bias correction is directly applied to temperature or precipitation data, the proposed method by Watanabe et al (2012) first corrects the statistical...
parameters for the baseline period, and then also corrects the projected temperature or precipitation by employing quantile-based mapping methods with the corrected statistical parameters. For temperature, the procedure for correcting the statistical parameter is as follows:

\[
\mu_t = \mu_o + \mu_p - \mu_b
\]

\[
\sigma_t = \frac{\sigma_p \sigma_o}{\sigma_b}
\]

where \(\mu\) and \(\sigma\) are the mean and standard deviation, respectively, and the subscripts \(o, p, b, \) and \(c\) represent the observation, projection, baseline, and correction, respectively. Then, the temperature data is corrected using the bias-corrected \(\mu\) and \(\sigma\) as follows:

\[
x_t = F^{-1}(F(x_p; \mu_p, \sigma_p; \mu_o, \sigma_o))
\]

In this equation, \(F\) is the cumulative distribution function (CDF) of the normal statistical distribution for temperature.

A similar correction procedure is used for the precipitation, but the zero values of precipitation are excluded first before the estimation of statistical parameters. The mean and coefficient of variation (CV) are corrected as follows:

\[
\mu_t = \frac{\mu_p \mu_o}{\mu_b}
\]

\[
CV_t = \frac{CV_p CV_o}{CV_b}
\]

Then, two statistical parameters, \(\alpha\) (shape) and \(\beta\) (scale), are estimated using the bias-corrected mean and CV. Finally, the precipitation is calculated from the corrected parameters based on the two-parameter gamma distribution. For more details on this correction method and procedure, please refer to Watanabe et al. (2012).

\[
x_t = F^{-1}(F(x_p; \alpha_p, \beta_p; \alpha_o, \beta_o))
\]

Note that the bias correction process here is implemented on the monthly temperature and precipitation data. After correction, the warm bias over Northwest China and the cold bias over other regions, especially the Tibetan Plateau, become much smaller (figure S2). The temperature climatology is much closer to the observation when compared with the uncorrected result (figure S1). The overestimation of precipitation over most regions in China is also corrected appropriately. Additionally, the corrected standard deviation for temperature and the CV for precipitation are also considerably closer to the observations.

2.3. Drought metric

The standardized precipitation evapotranspiration index (SPEI), proposed by Vicente-Serrano et al. (2010), is selected as the primary drought metric in this study. This index is constructed based on the supply and demand concept of the water balance equation for multiple time scales. The SPEI with a time scale of three months, which can reflect the variations in the meteorological droughts well (Chen and Sun 2015b), is mainly investigated in this study. The sophisticated Penman-Monteith method is adopted for the evaporation-transpiration (ET) calculation, which can account for changes in such parameters as available energy, humidity, and wind speed. The net radiation in the ET calculation is represented by the difference between the simulated net shortwave and longwave radiation from the CESM1. The simulated surface relative humidity and wind speed from CESM1 are also employed here. Note that the SPEI values for the future are calculated basing on the coefficients of log-logistic distribution resultant from the present period. In this study, in the categorization of drought grade by SPEI (table S1; Chen and Sun 2015b), the values less than −1.0, −1.5, and −2.0 represent moderate, severe, and extreme drought, respectively, at a given location.

2.4. Estimations of the probability ratio, avoided impacts, and population exposure

The probability ratio (PR) for the occurrence of droughts of different grades is calculated as \(P_I/P_0\) (Stott et al. 2004, Chen and Sun 2017a); where \(P_0\) is the probability of SPEI reaching a specific intensity in the present day and \(P_I\) is the corresponding probability in the 1.5 °C or 2.0 °C warmer future. Additionally, the impact of droughts that are avoided at the 1.5 °C warmer climate compared with 2.0 °C warmer climate is estimated as follows:

\[
AI = \frac{C_{I,0} - C_{I,5}}{C_{I,0}} \times 100\%
\]

where \(AI\) is the avoided impact, \(C_{I,5}\) and \(C_{I,0}\) are the changes under the 1.5 °C and 2.0 °C warming levels, respectively, compared to the present day.

The population exposure to drought is defined as the number of people exposed to moderate, severe, and extreme droughts; that is, the frequency of these droughts multiplied by the number of the exposed people (Sun et al. 2017, Chen et al. 2018, Li et al. 2018, Zhang et al. 2018). The population distribution in the year 2000 and for the future under different shared socioeconomic pathways (SSP) from 2010 to 2100 (Jones and O’Neill 2016) are employed to investigate the changes of population exposure at the 1.5 °C warming level compared with the 2.0 °C warming level. This population dataset is acquired from: https://www2.cgd.ucar.edu/sections/tss/iam/spatial-population-scenarios.

3. Results

3.1. Drought occurrence changes in response to 0.5 °C of additional warming

We first evaluate the changes in the occurrence probability of droughts from the present day (1986–2005) to each of the 1.5 °C and 2.0 °C scenarios at the end of the 21st century (2081–2100). The
avoided impacts if the warming is limited from 2.0 °C to 1.5 °C across China are also calculated (figure 1). The statistical significance for the avoided impact is calculated with a two-sided t-test at the 95% confidence level. Most regions over northern China, including Northeast China (NEC), North China (NC), Northwest China (NWC), and the Tibetan Plateau (TP) (please refer to figure S6 for more information on the subregions), present obviously widespread drying trends under both the 1.5 °C and 2.0 °C climates with significantly more drying at 2.0 °C compared to 1.5 °C. In contrast, the regions south of the Yangtze River valley display a decreasing trend of the occurrence probability of droughts under the 1.5 °C scenario but exhibit a weaker change than the drying trend over northern China. There are almost no differences between the 1.5 °C and 2.0 °C scenarios for this region, implying a weak climate response to the additional 0.5 °C warming in the future over this region.

In the context of a regional risk assessment, spatially aggregated mean changes are generally more helpful to investigate the risk of a particular region than a specific grid cell impacted by climate change. Our estimations show that the area-weighted mean of the occurrence frequency of droughts in a 1.5 °C warmer world increases by approximately 52% (48% ~ 62% for the range of the 25th and 75th quartiles of the ensembles, representing uncertainty from the internal climate variability) in China with respect to the present day. There is a strong increase in the drought occurrences in response to the additional 0.5 °C warming; the frequency is evaluated to increase by approximately 77% (73% ~ 88%) with respect to the present day when the GMST increases by 2.0 °C. The largest increasing magnitude of drought events is observed over the TP region with an increase of approximately 76% (67% ~ 91%) under the 1.5 °C warmer climate and almost double under the 2.0 °C warmer climate. The next highest increase is in NC, where drought events increase by approximately 46% (27% ~ 69%) in the 1.5 °C warming scenario and 68% (56% ~ 92%) in the 2.0 °C warming scenario. Meanwhile, weak decreases are projected over the regions of South China (SC) and Southwest China (SWC).

We used formula (7) to quantify the avoided impacts caused by droughts in the 1.5 °C warmer future compared with the 2.0 °C warmer future (figure 1(c)). Clearly, the significant increase of

Figure 1. Changes in the occurrence probability ratio of droughts in the (a) 1.5 °C and (b) 2.0 °C warmer climate scenarios compared to the present day. Values greater than 1.0 represent an increase in the drought occurrence, while values less than 1.0 indicate a decrease. (c) The avoided increase of drought events in response to 0.5 °C less warming. The dotted areas are statistically significant at the 5% level according to the two-sided t-test. (d) Regional aggregated means of the avoided impacts for different droughts over China. The error bars indicate the corresponding 25%–75% uncertainty ranges from the model internal variability. Units of avoided impact: %.
drought events over most regions of northern China could result in a substantial increase in the impacts of drought, especially for the regions of NEC, NWC, and TP. Therefore, the decrease in warming of 0.5 °C will help to significantly reduce the impacts caused by droughts in these regions. While the regions south of the Yangtze River valley will experience a decreased impact, mainly due to the decrease of droughts in response to the additional warming. The estimation of the aggregated mean change shows that the decrease in warming of 0.5 °C, if the global warming is limited to 1.5 °C instead of 2.0 °C, will help to avoid approximately 9% (5% ~ 14%) of the increase in drought occurrence in China (figure 1(d)).

To illustrate the benefits of limiting the warming to 1.5 °C or 2.0 °C, we further investigate the frequency changes in moderate drought, severe drought, and extreme drought events (figures S3–S5). A similar spatial pattern of changes in the occurrences of moderate droughts is observed compared with the changes in all droughts (figure 1) across China with increases over the northern regions and decreases south of the Yangtze River valley. A relatively larger magnitude of increase is observed in the change of the severe drought frequency, especially in the change of the extreme drought occurrence across China under both the 1.5 °C and 2.0 °C warmer climates. Further estimations show that if the global warming is limited to 1.5 °C instead of 2.0 °C, the occurrence risks of moderate, severe, and extreme drought events can be reduced by approximately 3% (~3% ~ 4%), 4% (~2% ~ 8%), and 8% (0 ~ 19%), respectively. In summary, the changes in the extreme droughts exhibit a relatively stronger response to the additional warming over China.

We also examined the avoided impacts of the different droughts for subregions over China due to the 0.5 °C decrease in warming (figure S6). Clearly, the occurrence risk of extreme droughts is estimated to decrease more than that of both moderate and severe droughts over most regions of China. Among the subregions, the avoided impacts of extreme droughts are greatest in TP, SWC, and NEC, which are approximately 21% (~1% ~ 39%), 21% (~10% ~ 31%), and 19% (~1% ~ 36%), respectively. For the regions of southern China, including EC, SC, and SWC, both moderate droughts and severe droughts decrease, while extreme droughts show an increase in response to the additional warming. Briefly, most regions of China would suffer from a substantially elevated risk of extreme drought events and their impacts, as induced by the additional 0.5 °C warming in the future.

3.2. Drought intensity change in response to 0.5 °C of additional warming
The intensity of a specified drought event is identified as the mean value of SPEI that exceeds a predefined threshold. For example, the intensity of the severe drought event is defined as the average of all monthly SPEI which less than −2.0 for each grid across China.

Different from the changes in drought occurrences, the intensity of all droughts shows a significant increase across China under both the 1.5 °C and 2.0 °C warming climates, but there is a relatively stronger increase under the 2.0 °C scenario (figure 2). Changes in the regional aggregating means over China show that the intensity increases by approximately 9% (7% ~ 10%) in the 1.5 °C warming scenario compared to the present day and approximately 13% (11% ~ 15%) in the 2.0 °C warming scenario. The largest increase occurs over NC in these two scenarios, and the majority of this region experiences a substantial increase, over 20% more, with respect to the present day. The estimation shows that the drought intensity over this region will increase by approximately 10% (9% ~ 13%) in the 1.5 °C warming scenario and approximately 15% (11% ~ 18%) in the 2.0 °C warming scenario. Additionally, NC is also the largest center of increasing drought frequency in response to the warming. Thus, the dry condition over this region would be further aggravated with the warming in the future.

In response to the 0.5 °C of additional warming, droughts will be more severe. Further assessment shows that this increase in the drought intensity is mainly associated with the substantial increase of the intensity of extreme drought events, while relatively smaller impacts can be attributed to both moderate and severe drought events. The regional aggregated means exhibit about 3.8% (1.5% ~ 4.3%) decrease in the drought intensity over China if the warming is limited to 1.5 °C instead of 2.0 °C (figure 2(d)). The intensity of extreme drought events is also reported to decrease by approximately 3.7% (1.8% ~ 5.2%), while the decreases in response to the additional warming are only 0.2% (0.1% ~ 0.4%) and 0.2% (0.1% ~ 0.3%) for moderate and severe droughts, respectively. This increasing trend of drought intensity (including moderate, severe, and extreme events) is robust across different regions of China (figure S7). Thus, the decrease in warming of 0.5 °C could substantially reduce the impacts produced by the change of drought severity across China, especially for extreme drought events.

3.3. Changes in population exposure to droughts
There is increasing evidence that the frequency and intensity of drought events has increased significantly over most regions in China as a result of continuous anthropogenic climate change (e.g. Chen and Sun 2017b, Chen et al 2018). Our findings are in accordance with these previous assessments and illustrate the substantial increase in the likelihood of droughts in the 1.5 °C and 2.0 °C warmer climates with respect to the present day, particularly for extreme drought events. The impacts of these increases in droughts pose a large threat to different sectors. In this section, the differences in the impacts
on populations imposed by the droughts are assessed in China for the 1.5°C and 2.0°C warming scenarios. According to the assessments from the CMIP5 model simulations, a stable increase of 1.5°C (2.0°C) GMST above the preindustrial level will occur around the year 2030 (2050) (Jiang et al 2016, Chen and Sun 2018). The populations in the years 2000, 2030, and 2050 from SSP1 (shared socioeconomic pathway) are thus used to represent the population in the present day, in the 1.5°C warming scenario and the 2.0°C warming scenario, respectively. The estimation shows that the population in China will reach a peak around the year 2030 and then decrease thereafter. In other words, there will be a smaller population in the year 2050, decreased by approximately 10%, compared to the population in the year 2030 in China.

Figure 3 illustrates the spatial distribution of the population exposure to droughts in the present day, and the 1.5°C and 2.0°C warmer climates. Clearly, a high population exposure to droughts is mainly concentrated over the eastern regions of China, especially in the NC and EC regions, as well as in the Sichuan Basin. While a low population exposure is reported over western China, especially in the TP and the south of Xinjiang. There is no significant change in this pattern of population exposure to droughts paralleling the GMST increase. However, the exposures exhibit a substantial increase in response to additional warming in the future. The aggregated population exposure in the present day is 31 million, which increases to 41 million in the 1.5°C warming scenario and 42 million in the 2.0°C warming scenario.

We further compare the population exposure to different droughts in these scenarios (figure 3(d)). The exposure to moderate and severe droughts first increases in the 1.5°C compared to that in the present day but then decreases in the 2.0°C warmer climate. Meanwhile, the population exposure to extreme droughts exhibits a persistent increase with the GMST increase. Moderate droughts account for the most exposure with 65% of the total exposure in the present day and 53% and 48% in the 1.5°C and 2.0°C warming scenarios, respectively. In comparison, the ratios of severe and extreme droughts increase; in particular, the extreme droughts account for 18% and 24% of the total exposure in the two warming scenarios, 1.5°C and 2.0°C, respectively. Therefore, our results indicate that in the future, the risks of the population exposure to droughts increase substantially in China, which can be attributed to the increase of extreme droughts in particular.

We used formula (7) to further evaluate the potential reduction of the population exposure to different droughts if the global warming is limited to 1.5°C instead of 2.0°C (figure 4). We found that the
Figure 3. Spatial patterns of the population exposure (in thousands) to droughts in (a) present day, (b) 1.5 °C, and (c) 2.0 °C warmer climates. (d) Regional aggregated population exposure to different droughts in China (units: million).

Figure 4. Spatial distribution of the potential reduction of the population exposure to different droughts in China due to 0.5 °C less warming at the 1.5 °C climate instead of the 2.0 °C warmer climate. Units: %.
exposure to moderate droughts exhibits an almost entirely decreasing pattern across China, except for some grids over the northern region of China, in response to the 0.5°C of additional warming. The aggregated mean suggests that the population exposure to moderate droughts is reduced by approximately 12% as a result of the 0.5°C of additional warming, although the occurrence probability of moderate droughts increases across China. Thus, this decrease in exposure mainly results from the decreasing population of China in the future. A similar spatial pattern is observed in the exposure to severe droughts; however, the land fraction with increased exposure increases, especially over the northern region of China. Different from the changes in moderate and severe droughts, the exposure to extreme droughts exhibits a widespread increase across China due to the additional warming. The increases in the NEC, NC, EC, and SWC regions are apparent, in which the exposure over most grids is estimated to increase by greater than 20% at 2.0°C compared to 1.5°C. Considering China altogether, in comparison to the 2.0°C warmer future, the decrease in warming of 0.5°C in the 1.5°C warmer future will help to reduce approximately 17% of the exposure to extreme droughts. Notably, the combination of moderate and severe droughts dominates the overall pattern of the total exposure over China, but the substantial increase of the exposure to extreme droughts indicates the importance and necessity to pursue efforts to limit the global warming to 1.5°C.

4. Conclusions

Our study examines the changes in droughts in China under stabilized 1.5°C and 2.0°C warmer climates with respect to the present day, using a set of coupled simulations with CESM. The results indicate that if the warming limited to 1.5°C or 2.0°C, the projected significant increase of drought occurrence dominates the northern region of China, while a decreasing trend prevails over the regions south of the Yangtze River valley. Different from the change in the drought frequency, the intensity is projected to significantly increase across China under a 1.5°C or 2.0°C warmer climate with a stronger increase at 2.0°C compared to 1.5°C. In particular, the increase is stronger for severe and extreme droughts across China, which exhibit a significant increase in both frequency and intensity. We have noted that the precipitation over China is projected to substantially increase under both the 1.5°C and 2.0°C scenarios (figure S8). However, the precipitation cannot balance the increase in the temperature/evaporative demand, leading to the significant increase in the drought risk relative to the present day. This result suggests an increased role of the temperature on the drought occurrence in China in the future.

In comparison to the 2.0°C warmer future, the decrease in warming of 0.5°C in the 1.5°C warmer future will help to avoid obvious increases in the frequency and intensity of droughts in China. Our assessments show that the 0.5°C decrease in warming can reduce approximately 9% (5% ~ 14%) of the increase in the drought occurrence over China if the global warming is limited to 1.5°C instead of 2.0°C. A relatively strong response is observed in the change of extreme droughts, which is reduced by approximately 8% (0 ~ 19%) in the decreased warming scenario, while a relatively weak response is observed for the moderate (3%) and severe (4%) droughts. Similar changes are observed in the drought intensity. Thus, droughts in China will become more extreme with warming in the future.

The projected increase in droughts in China leads to a significant increase in the population exposure to droughts in the future. The exposure increases from 31 million in the present day to 41 million in 1.5°C warming scenario and 42 million in the 2.0°C warming scenario. In response to the 0.5°C additional warming, the aggregated assessment shows that the population exposure to moderate droughts will be reduced by approximately 12%, despite the occurrence increase over China. Different from moderate droughts, the exposure to extreme droughts exhibits an obvious increase, which is an increase of approximately 17% as a result of the 0.5°C additional warming. The mitigation of warming by 0.5°C is thus urgently needed, because it might yield significant reductions in exposure for some regions, especially the exposure to extreme droughts.

Some new insights, including the strong response of drought increase to 0.5°C additional warming as well as its associated population exposure in the future across China, can be derived from our analyses. However, there are also some remaining limitations. For example, the uncertainties for the changes of droughts as well as the population exposure are large over China, which are mainly sourcing from internal climate variability (Lin et al. 2018) and also relating to the methods used in this study. While much comparison work remains to be done, we believe the bias correction method used in this study has relatively stronger merits in the impact assessment studies than the others, because this method proposed by Watanabe et al. (2012) can successfully conserve the intrinsic characteristics of the variables before and after bias correction. Additionally, our assessments in this study are in line with the results from the other global climate models (Chen et al. 2018) as well as the regional climate model simulations (Sun et al. 2017). Thus, the changes in droughts and the associated population exposure in the future are robust over China.
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