Replies to Referee #2

Projected increases in magnitude and socioeconomic exposure of global droughts in 1.5 °C and 2 °C warmer climates

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We thank the anonymous reviewer for the constructive comments and suggestions. We have provided detailed responses to each comment below and will revise the manuscript accordingly. For clarity, comments are given in *italics*, and our responses are given in plain text.

Authors' responses

Legend

Reviewer's comments

Authors' responses

General Comments

In summary, motivated by the 2015 Paris Agreement proposal, this manuscript calculated global 3-month Standardized Precipitation Evapotranspiration Index (SPEI-3) based on 13 CMIP5 GCM simulations under three RCP scenarios (RCP2.6/4.5/8.5) during 1976-2100, quantified changes in global drought duration, severity and occurrence under a bivariate framework, and analyzed the drought exposures of populations and regional GDP under 3 shared socioeconomic pathways (SSPs) in future 1.5 and 2-degree warming worlds. Generally, this well written manuscript is able to portray drought evolution with different warming trajectories and provides information for climate adaptation strategies. Here I list several questions below and suggest acceptance of the manuscript after minor revision.

We appreciate that the reviewer is favor of our manuscript. Please find our specific responses below.

Minor Comments

(1) P7, L19-20. How do you determine the year in which a specific warming target is achieved? I suppose you select the median year of the 30-year period with surface

temperature closest to the warming target for each RCP (not for each RCP-GCM combination), so that the reaching year is the same for all 13 GCMs under a prescribed RCP scenario. The authors should clarify this.

Reply: Sorry for that we did not clearly clarify this point. Yes, the period is determined based on multi-model ensemble mean of temperature. Thus, the reaching year is the same for all 13 GCMs under a specific RCP scenario. However, instead of using median year of the 30-year period, we used the 30-year running-mean. In other words, we selected the 30-year period with mean temperature closest to the warming target for each RCP. This will be clarified in the revised manuscript (in Section 2.2).

(2) Figure 1a. I've noticed that the determined years under both scenarios (RCP2.6 and RCP8.5) are the first year (2020) of the whole period. Is it possible that for some GCM future projections, 1.5-degree warming (or even higher) has already been reached even at the beginning of the simulation period? If so, maybe it could affect the results in this manuscript.

Reply: Thanks for this comment. We acknowledge that a few individual projections among the multi-model ensemble slight exceed the 1.5-degree warming at the beginning of the simulation period (i.e. BNU-ESM, CanESM2, GFDL-CM3 and MIROC-ESM-CHEM; Table R1). We will discuss this comment as follows:

To fully consider the robustness of the results, we use the warming level of multi-model ensemble mean to serve as the warming trajectory. Firstly, comparing to the method of determining warming level by individual model output, the use of multi-model ensemble mean method involves more future projections/GCMs and thus guarantees the reliability of the conclusions (Chen et al., 2011; Mehran et al., 2014). This multi-model ensemble mean method is also consistent with some previous studies (Liu et al., 2018a, 2019; Su et al., 2018). Secondly, the application of the multi-model ensemble mean method keeps the consistency of the sample size under each RCP and for each warming level. This can exclude the differences originated from the sample size when assessing different warming level impacts or evaluating RCP uncertainty. It is true that different warming level calculating methods can result in divergent model ensembles and may thus affect the results. For example, some studies (Sanderson et al., 2017; Lehner et al., 2017) used single model to conduct climate warming impact assessments, while some studies (James et al., 2017; Thober et al., 2018) employed pooled future projections (i.e. 1.5/2.0°C) to perform analyses without considering RCP discrepancies. Future studies may explore the impacts of different warming level calculation methods, but it is beyond the scope of the current study.
All the information above will be added in the Discussion Section of the revised manuscript.

Table R1 Models with global warming higher than 1.5°C in the 2006 year (°C)

MODEL	RCP2.6	RCP4.5	RCP8.5
BNU-ESM	1.503	1.583	1.540
CanESM2	1.594	1.479	1.692
GFDL-CM3	1.720	1.734	1.741
MIROC-ESM-CHEM	1.646	1.500	1.643

Chen, J., Brissette, F. P., Poulin, A., and Leconte, R.: Overall un- certainty study of the hydrological impacts of climate change for a Canadian watershed, Water Resour. Res., 47, W12509, https://doi.org/10.1029/2011wr010602, 2011.

James, R., Washington, R., Schleussner, C. F., Rogelj, J., & Conway, D. (2017). Characterizing half‐a‐degree difference: a review of methods for identifying regional climate responses to global warming targets. Wiley Interdisciplinary Reviews: Climate Change, 8(2), e457.

Lehner, F., Coats, S., Stocker, T. F., Pendergrass, A. G., Sanderson, B. M., Raible, C. C., and Smerdon, J. E.: Projected drought risk in 1.5°C and 2°C warmer climates. Geophys. Res. Lett., 44: 7419-7428, 2017.

Liu, W., Sun, F., Lim, W. H., Zhang, J., Wang, H., Shiogama, H., and Zhang, Y.: Global drought and severe drought-affected populations in 1.5 and 2 °C warmer worlds. Earth Syst. Dynam., 9:267-283, 2018a.

Liu, W., & Sun, F. Increased adversely-affected population from water shortage below normal conditions in China with anthropogenic warming. Science Bulletin, 64(9), 567-569, 2019.

Mehran, A., AghaKouchak, A., and Phillips, T. J.: Evaluation of CMIP5 continental precipitation simulations relative to satellite- based gauge-adjusted observations, J. Geophys. Res.- Atmos., 119, 1695–1707, https://doi.org/10.1002/2013jd021152, 2014.

Sanderson, B. M., Xu, Y., Tebaldi, C., et al.: Community climate simulations to assess avoided impacts in 1.5 and 2 °C futures. Earth Syst. Dynam., 8, 827-847, https://doi.org/10.5194/esd-8-827-2017, 2017.

Su, B., Huang, J., Fischer, T., Wang, Y., Kundzewicz, Z. W., Zhai, J., and Tao, H.: Drought losses in China might double between the 1.5° C and 2.0° C warming. P. Natl. Acad. Sci. USA., 115(42), 10600-10605, 2018.

Thober, S., Kumar, R., Wanders, N., Marx, A., Pan, M., Rakovec, O., ... & Zink, M. (2018). Multi-model ensemble projections of European river floods and high flows at 1.5, 2, and 3 degrees global warming. Environmental Research Letters, 13(1), 014003.

(3) Figure 9, 10, S2 and Discussion Section. There are several countries (e.g. the United States) will experience a decrease in POP and GDP fraction exposing to more frequent severe droughts under the 2-degree warming level compared to 1.5-degree. I will be appreciated if the author could provide possible reasons considering the increasing drought risks in these countries.

Reply: Thanks for this suggestion. Actually, countries that experience a decrease in POP and GDP exposure fraction under the 2°C warming can be attributed to the decreasing land fraction exposing to more frequent droughts. Here, we listed some example countries in Table R2 to analyze the reasons. We will add more analysis and revised clarifications in the revised manuscript (Section 3.4) as follows:

It should be noted that when climate warming climbing from 1.5°C to 2.0°C, there are some spatial heterogeneity with regards to drought exposures variations. Specifically, drought exposures for some countries (i.e., Canada) can be slightly decreased in 2°C warming level compared to 1.5°C warming level. This decrease in POP and GDP exposure fraction can be attributed to the decreasing land fraction exposing to more frequent droughts. For example, the land fraction suffering more frequent severe droughts in Canada will decrease (-12.77%) in 2.0°C warming level comparing to 1.5°C warming under RCP2.6 scenario. In other words, the additional 0.5°C warming will not lead to drought risk deterioration globally, partly due to the increasing column precipitable water with warming environment (Dong et al., 2019; Yin et al., 2019), although it holds for the majority of global land masses. Anyway, the spatial heterogeneity should be paid attention especially when assessing the climate change impacts on extreme events at regional or local scales (Liu et al., 2018b).

Table R2 Several countries suffering decreasing POP and GDP exposure

Land fraction exposing to more frequent droughts									
	1.5°C			**2°C**			**2-1.5°C**		
Country	**RCP2.6**	**RCP4.5**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP8.5**
Canada	68.35%	68.82%	71.56%	55.58%	63.36%	66.92%	-12.77%	-5.46%	-4.63%
United States	86.17%	78.93%	86.89%	85.44%	80.02%	79.84%	-0.72%	1.08%	-7.05%
Colombia	85.71%	84.62%	79.12%	75.82%	93.41%	85.71%	-9.89%	8.79%	6.59%
Japan	62.16%	56.76%	62.16%	59.46%	62.16%	62.16%	-2.70%	5.41%	0.00%
Population (million)									
	1.5°C			**2°C**			**2-1.5°C**		
Country	SSP1	SSP2	SSP5	SSP1	SSP2	SSP5	SSP1	SSP2	SSP5
Canada	7.97	7.91	8.27	10.50	8.95	9.57	2.53	1.04	1.30
United States	59.13	58.82	60.75	73.56	64.86	68.20	14.43	6.05	7.45
Colombia	9.41	9.67	9.33	10.20	10.84	9.88	0.79	1.17	0.56
Japan	17.82	17.63	18.12	15.48	16.53	17.95	-2.34	-1.11	-0.17
GDP (billion USD, 2010price PPP)									
	1.5°C			**2°C**			**2-1.5°C**		
Country	**SSP1**	**SSP2**	**SSP5**	**SSP1**	**SSP2**	**SSP5**	**SSP1**	**SSP2**	**SSP5**
Canada	373.60	373.74	398.99	719.26	499.22	563.41	345.67	125.48	164.41
United States	3639.14	3517.35	3759.94	6699.26	4554.66	5118.33	3060.12	1037.32	1358.38
Colombia	192.32	184.47	191.51	617.84	296.93	311.37	425.52	112.46	119.86
Japan	575.07	553.76	590.57	873.40	620.73	730.21	298.33	66.97	139.63
Population Exposure Fraction									
	1.5°C			**2°C**			**2-1.5°C**		

Country	SSP126	SSP245	SSP585	SSP126	SSP245	SSP585	SSP126	SSP245	SSP585
Canada	99.25%	98.88%	98.77%	99.14%	98.32%	98.70%	-0.11%	-0.56%	-0.07%
United States	99.84%	99.60%	99.85%	99.82%	99.85%	99.84%	-0.02%	0.26%	-0.01%
Colombia	84.83%	77.64%	46.20%	57.22%	98.90%	80.06%	-27.61%	21.26%	33.87%
Japan	99.72%	97.95%	99.78%	72.89%	98.65%	99.78%	-26.82%	0.70%	0.00%
					GDP Exposure Fraction				
		1.5°C			**2°C**			**2-1.5°C**	
Country	**SSP126**	**SSP245**	**SSP585**	**SSP126**	**SSP245**	**SSP585**	**SSP126**	**SSP245**	**SSP585**
Canada	99.26%	98.89%	98.79%	99.15%	98.34%	98.72%	-0.11%	-0.55%	-0.07%
United States	99.84%	99.59%	99.85%	99.82%	99.85%	99.84%	-0.02%	0.26%	-0.01%
Colombia	84.85%	77.67%	46.27%	57.27%	98.90%	80.09%	-27.58%	21.23%	33.82%
Japan	99.72%	97.95%	99.78%	72.89%	98.65%	99.78%	-26.82%	0.70%	0.00%

Dong, W., Lin, Y., Wright, J. S., Xie, Y., Yin, X., & Guo, J. Precipitable water and CAPE dependence of rainfall intensities in China. Climate Dynamics, 52(5-6), 3357-3368, 2019.
Liu, W., Lim, W. H., Sun, F., Mitchell, D., Wang, H., Chen, D., ... & Fischer, E. Global freshwater availability below normal conditions and population impact under 1.5 and 2 C stabilization scenarios. Geophysical Research Letters, 45(18), 9803-9813, 2018b.
Yin, J., Gentine, P., Guo, S., Zhou, S., Sullivan, S. C., Zhang, Y., ... & Liu, P. Reply to 'Increases in temperature do not translate to increased flooding'. Nature communications, 10(1), 1-5, 2019.

(4) P10, L26. Eq. (5) should be Eq. (11)?

Reply: Sorry for the mistake. Eq. (5) will be corrected as Eq. (11) in the revised manuscript.

(5) As the authors mentioned in Section 2.1 that RCP2.6 is associated with SSP1, I suggest the author use SSP126 instead of RCP2.6 when talking about future drought risks. Same with SSP245 and SSP585.

Reply: Thanks for this suggestion. We will revise the statement in the manuscript.

(6) Relative to huge gaps in drought characteristics for two warming targets, results under three RCP scenarios seems to have few differences (e.g. Figure 6). Maybe the authors could explain the reason in Discussion Section, or explore the possible causes in future studies.

Reply: Thanks for this insightful comment. We will add the discussion as follows in the revised manuscript:

It is well-known that the warming trajectories are dependent on RCP scenarios. In other words, different RCP scenarios correspond to various temperature levels for the fixed time period. However, this study fixed the warming level. It can be expected that the differences among RCP scenarios are largely reduced. Nevertheless, the complex circulation system can still result in some differences in hydro-meteorological variables (e.g., precipitation, wind speed and relative humidity) among RCP scenarios, even at the same warming level, because they are not linearly related to the warming temperature. Since drought conditions are evaluated by using such hydro-meteorological variables, those differences at the same warming level can lead to variations in drought evolutions. Furthermore, drought variations under three RCP scenarios are even to some extent significant at the regional or national scales. For example, when the warming level increasing from 1.5°C to 2.0°C, the GDP exposure for the Colombia will decrease at the SSP126 scenario while it will increase at the SSP585. Future studies may explore their potential physical mechanisms (i.e., connecting drought evolution with land-atmosphere interactions).