Response to the Editor

First of all I would like to thank authors and reviewers for their contribution to Earth System Dynamics. As the authors could read, the reviewers valued the work and consider that it is worthwhile of publication, but they formulate a good number of comments. Some are requests for specification of methodological details, which will be surely satisfied. However, the reviewers also expressed a number of bigger concerns.

Thank you. In the revised manuscript, each of comments has been carefully addressed (*please find the point to point response below*). In the acknowledgement section, we added: "*We thank the Editor (Michel Crucifix), Dimitri Defrance and an anonymous reviewer for their helpful comments*". (*Line 452-453 in the latest clean version*).

Among others,

• Review 1 expresses concerns about systematic biases, and the authors respond in discussion paper that "In this case, application of bias correction method(s) towards the historical and future periods would be somewhat redundant." I am not convinced by this justification. Both the physics and the impacts of precipitation and drought are highly non-linear.

We would like to clarify our point. It is common to find systematic biases in climate model output, where application of bias-correction measures would be helpful for adjusting the "*absolute value*" of a target climate model output (*e.g., precipitation or temperature*) so that its statistics (*e.g., distribution*) would be consistent with that of the observations. Nonetheless, recent climate change studies have investigated and demonstrated that the calculated "*change*" (*between the historical and future periods*) with and without bias-correction is quite similar (*e.g., Sun et al., 2011; Maraun, 2016*). This is because similar statistical adjustment made to the historical and future periods cancelled off one another. In addition, the climate model outputs are constrained by energy balance (*i.e., radiative, latent heat, sensible heat fluxes and heat storage of the earth system*). Whilst we are confident that the application of raw climate model output (*short- and long-wave radiation, air temperature, wind, humidity, atmospheric pressure, precipitation*) as part of our methodology (*Equation 3 in Section 2.3*) is consistent with the energy balance of a climate model, we not convinced enough to use existing bias correction measures To our knowledge, existing bias correction measures do not explicitly considers the energy balance of climate model output. We are also not quite sure whether the physical relationships among different meteorological variables (*i.e., air temperature, precipitation, humidity*) used can still be hold after bias correction. For these reasons, we make use of the raw climate model output in current analysis (*please also see our response to the third major comment of reviewer 1*).

We think that future innovation with proper account for both statistics and energy balance (*and also the multivariable relationships*) of climate model output in new bias-correction methodology for handling the highly non-linear outcomes (*as the Editor noticed*) should be a subject of scientific interest. Because of this possibility, we removed the phrase "*…would be somewhat redundant …*" from our earlier response.

In response, we revised Section 2.3 to clarify the rationale of our methodology. We also discussed the feasibility of using existing bias correction measures and point out that future innovation in bias correction methodology should be a subject of scientific interest in Section 4.

Reference:

Sun,F., Roderick, M.L., Lim, W.H., and Farquhar, G.D.: Hydroclimatic projections for the Murray-Darling Basin based on an ensemble derived from Intergovernmental Panel on Climate Change AR4 climate models, Water Resource Research, 47, W00G02, 2011

Maraun, D.: Bias correcting climate change simulations – a critical review, Curr. Clim. Change Rep., 2, 211-220, 2016

• Reviewer 2 expresses concerns about resolution, and the authors reply by providing the simulation context which has forced this choice of resolution.
Please find our response to Reviewer 2 in the latter part of this word document. Thank you.

We all fully understand that some methodological choices are forced by the circumstances, techniques and resources available. However the authors consider their paper to be targeted to policy makers. They therefore endorse a role of expert, and this is the expert's job to synthesize the caveats attached to their study, with regard to possible use of their study for policy decisions. This needs to be done in plain and clear language.
In the revised manuscript, we synthesized helpful feedbacks from the editor and reviewers into the manuscript. We used plain language throughout the manuscript (*please see the marked version*) in order to convey clear scientific findings for the policymakers to develop informed decision. Thank you.

As a side note, the authors state that they "first generalized the multi-model results using the multi-model ensemble mean". The word "generalized" should be replaced by "synthesised", as a multi-ensemble mean is by no mean a generalisation.
Good idea. In response, we replaced the word "*generalized*" with "*synthesized*" wherever appropriate in the revised manuscript and our response to reviewers. Thank you..

The authors are now invited to submit their revised document, which will be sent again to the reviewers.
Thank you.

Response to review comments - RC1:

This article talks about the drought evolution (duration, intensity and frequency) due to the climate change in a 1.5 (2^{o}C) scenarii defined by the COP21. It gives an estimation of the impacted people around the world. To obtain these results, the article uses outputs from eleven CMIP5 GCMs with the RCP4.5 and 8.5, the gridded population from SSP1 scenario and the Palmer drought severity index (PDSI). The transdisciplinary of this article is very interesting and show the human impacts due to the climate change. This paper is divided in 5 parts: an introduction that clearly defines the drought importance on the human society and the 1.5^{o}C (2^{o}C) scenario. The second part describes the data and the method but in this section, some corrections are required (see below). The results are well described and the discussion is interesting but some justifications could improve the limits of the method. I suggest publishing this article in ESD with major revision. The different remarks and suggestions are described below.
Thank you. In the revised manuscript, we clarified the justifications and methodology of this manuscript. In the acknowledgement section, we added: "*We thank the Editor (Michel Crucifix), Dimitri Defrance and an anonymous reviewer for their helpful comments*". (*Line 452-453 in the latest clean version*).

Major comment on the methodology

That is the major comment on your article and the bigger correction I demand. First, I find that you don't give enough details to justify the choose to use eleven-CMIP5 models and only 2 RCP scenarios (4.5 and 8.5). Data are available on about 30 models for RCP8.5 (e.g. Famien et al. ESD discussion November 2017) and available for RCP2.6 and 6 but with a reduced number of models. Are more simulations not better? I would like a justification of the models use.
We could have clarified the justification on the selection of climate models and climate scenarios as part of the methodology in the original version of this manuscript. A key step in current study is computation of PDSI using climate model outputs. It requires monthly simulated outputs, i.e., surface mean air temperature, surface minimum air temperature, surface maximum air temperature, air pressure, precipitation, relatively humidity, surface downwelling longwave flux, surface downwelling shortwave flux, surface upwelling longwave flux and surface upwelling shortwave flux; daily simulated outputs, i.e., surface zonal velocity component and meridional velocity component. Whilst a large number of climate models are available in the CMIP5 archive, we made use of those fully satisfied our data requirement. Among the RCP scenarios (*i.e., RCP2.6, RCP4.5, RCP6, RCP8.5*), the climate models under RCP4.5 and RCP8.5 scenarios are more complete relative to those under RCP2.6 and RCP4.5 scenarios (the reviewer also noticed this). In fact, recent studies have confirmed that the impacts of similar global mean surface temperature *(i.e., +1.5^{o}C, +2^{o}C worlds*) among the RCP scenarios are quite similar, implying that the global and regional responses to temperature and are independent of the RCP scenarios (*Hu et al., 2017; King et al., 2017*). These provide the scientific

justification for using the climate models under the RCP4.5 and RCP8.5 scenarios in current study. We settled at using 11 CMIP5 models under these scenarios.

In response, we clarified the justification of climate models and climate scenarios used in Line 128-135, as follows,

"...Recent studies have confirmed that the impacts of similar global mean surface temperature (i.e., 1.5°C and 2°C warmer worlds) among the Representative Concentration Pathways (RCPs) are quite similar, implying that the global and regional responses to temperature and are independent of the RCPs (Hu et al., 2017; King et al., 2017). Following this idea, we settled at using 11 CMIP5 models which satisfied the data requirement of PDSI calculation (see paragraph above) under RCP4.5 and RCP8.5. Following Wang et al. (2017) and King et al. (2017), we use the ensemble mean of these CMIP5 models and climate scenarios (RCP4.5, RCP8.5) to composite the warming scenarios (1.5°C and 2°C warmer worlds)..."

Reference:

King, A.D., Karoly, D.J., and Henley, B.J.: Australian climate extremes at 1.5°C and 2°C of global warming, Nat. Clim. Change, 7, 412-416, doi:10.1038/nclimate3296, 2017.

Schleussner, C., Lissner, T.K., Fischer, E.M., Wohland, J., Perrette, M., Golly, A., Rogelj, J., Childers, K., Schewe, J., Frieler, K., Mengel, M., Hare, W., and Schaeffer, M.: Differential climate impacts for policy-relevant limits to global warming: the case of 1.5°C and 2°C, Earth Syst. Dynam., 7, 327-351, doi: 10.5194/esd-7-327-2016, 2016.

Wang, Z.L., Lin, L., Zhang, X.Y., Zhang, H., Liu, L.K., and Xu, Y.Y.: Scenario dependence of future changes in climate extremes under 1.5°C and 2°C global warming, Sci. Rep., 7:46432, doi:10.1038/srep46432, 2017.

Hu, T., Sun, Y., and Zhang, X.B.: Temperature and precipitation projection at 1.5 and 2°C increase in global mean temperature (in Chinese), Chin. Sci. Bull., 62, 3098-3111, 2017.

Secondly, in your study, all models have the same ponderation but if a model is a reverse signal, this result is not visible, to avoid this problem you can use a classification of model type as in Monerie et al, 2016 (10.1007/s00382-016-3236-y) or in Sgubin et al., 2017 (10.1038/ncomms14375.375). I think that the use of a classification is important to improve your results robustness.
Whilst it is possible to perform classification study, we have concern that it would shift away from the main focus of current study and our target audience (*i.e., international policy-makers*). This manuscript is prepared to inform climate policy-making hence we synthesised the impacts as much as possible. We also performed sufficient uncertainty analyses. For example, we first synthesised the multi-model results using the multi-model ensemble mean (*the left panels in Figures*

3, 5, 7 and 9), as many other studies did (*i.e., Mo et al., 2015; He and Soden, 2016*). We then quantified the different results/uncertainty among climate models using model consistency (*the right panels in Figures 3, 5, 7 and 9*) and boxplots (*Figures 4, 6, 8 and 10*). We characterized different impacts of severe droughts on population at continental scales using the multi-model ensemble mean and the corresponding uncertainty among climate models in Figures 11-13. We also discussed the uncertainties of this study in Section 4 (*Line 388-402 in the latest clean version*)

Reference:

Mo, K.C. and Lyon, B.: Global Meteorological drought prediction using the North American Multi-Model ensemble, J. Hydrometero., 16, 1409-1424, 2015.

He, J., and Soden, B.: A re-examination of the projected subtropical precipitation decline, Nature Climate Change, 17, 53-57, 2016.

My other remark (the more important correction) is due to your impacted study. You write in the discussion that the uncertainty of the model is important and the use of several models weaks the error. That is true but not sufficient. In some region, I think about West Africa, no models have the correct precipitations pattern. This problem is maybe present in other regions. I think this problem lead to a wrong result for the impact and this part must be corrected. The best solution is to unbiase the outputs of the model with e.g. a quantile/quantile method (univariate or multivariate) and observations. These outputs maybe exist now and can improve your interesting results. Another way is better describe the errors between the models and the current observations to be able to determine a confidence index for all regions. With a correction of the output or with a discussion of the local error from the model, the results will be robuster and you can eject the area where the confidence index is not sufficient.

We could have explained better about the methodology and the rational in the original version of the manuscript. It is common to find systematic biases in climate model output, where application of bias-correction measures would be helpful for adjusting the "*absolute value*" of a target climate model output (*e.g., precipitation or temperature*) so that its statistics (*e.g., distribution*) would be consistent with that of the observations. Nonetheless, recent climate change studies have investigated and demonstrated that the calculated "*change*" (*between the historical and future periods*) with and without bias-correction is quite similar (*e.g., Sun et al., 2011; Maraun, 2016*). This is because similar statistical adjustment made to the historical and future periods cancelled off one another. In addition, the climate model outputs are constrained by energy balance (*i.e., radiative, latent heat, sensible heat fluxes and heat storage of the earth system*). Whilst we are confident that the application of raw climate model output (*short- and long-wave radiation, air temperature, wind, humidity, atmospheric pressure, precipitation*) as part of our methodology (*Equation 3 in Section 2.3*) is consistent with the energy balance of a climate model, we not convinced enough to use existing bias correction measures To our knowledge, existing bias correction measures do not explicitly considers the energy balance of climate model output. We are also not quite sure whether the physical relationships among different meteorological variables (*i.e., air temperature, precipitation, humidity*) used can still be hold after bias correction. For these reasons, we make use of the raw climate model output in current analysis (*please also see our response to the first comment of the Editor*).

In response, we revised Section 2.3 to clarify the rational of our methodology. We also discussed the feasibility using bias-correction approaches and alternative confidence indices (*combine with thoughts kindly put forward by the reviewer*) in Section 4. Thank you.

Reference:

Sun,F., Roderick, M.L., Lim, W.H., and Farquhar, G.D.: Hydroclimatic projections for the Murray-Darling Basin based on an ensemble derived from Intergovernmental Panel on Climate Change AR4 climate models, Water Resource Research, 47, W00G02, 2011

Maraun, D.: Bias correcting climate change simulations – a critical review, Current Climate Change Reports, 2, 211-220, 2016

Hirabayashi, Y., Mahendran, R., Korala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H. and Kanae, S.: Global flood risk under climate change, Nature Climate Change, 3, 816-821, 2013

Koirala, S., Hirabayashi, Y., Mahendran, R., Kanae, S.: Global assessment of agreement among streamflow projections using CMIP5 model outputs, Environmental Research Letters, 9, 064017 (11pp), 2014

Some questions/remarks

In the abstract: I suggest adding some numerical results from the results and discussion part because of now the abstract is too qualitative.

Good point. In response, we added more quantitative results in the abstract (Line 32-37 in the latest clean version). Thank you.

Line 84: maybe add a reference for the longer duration

Done. Thank you.

Reference:

McKee, T.B., Doesken, N.J. and Kleist, J.: The relationship of drought frequency and duration of time scales, Eighth Conference on Applied Climatology, American Meteorological Society, Jan 17-23, Anaheim CA, PP. 179-186, 1993.

Line 101: Why do you use only the SSP1 scenario? That is right this is compatible with the 1.5^o scenarios (Line 135) but other SSP scenarios are also compatible with your climatic scenario. Have you an idea of the impacts of the different SSP scenarios on your results?

We used SSP1 scenario because it describes the storyline of a green growth paradigm with sustainable development and low challenges for adaptation and mitigation (*O'Neill et al., 2014, Climatic Change*). The +1.5^{o}C and +2^{o}C worlds clearly fit in this description and thus considered under the Paris Agreement 2015 (*UNFCCC Conference of the Parties 2015*). We clarified the use of SSP1 scenario as follows (*Line 241-248* in the latest clean version),

"…We repeat this estimation using the constant SSP1 population data in 2100 for the 1.5^{o}C and 2^{o}C warming worlds, which is consistent with the original proposal of Paris Agreement on stabilizing global warming for the specified targets by end of the 21st century. We used SSP1 scenario because it describes the storyline of a green growth paradigm with sustainable development and low challenges for adaptation and mitigation (Jones and O'Niell, 2016). The 1.5^{o}C and 2^{o}C warmer worlds clearly fit in this description and thus considered under the 2015 Paris Agreement (UNFCCC Conference of the Parties 2015; O'Niell et al., 2016)…"

Reference:

O'Neill et al.: A new scenario framework for climate change research: the concept of shared socioeconomic pathways, Climatic Change, 122, 387-400, 2014.

UNFCCC Conference of the Parties 2015: Adoption of the Paris Agreement, FCCC/CP/2015/10Add.11-32Paris

Line 153: Why do you use +-0.2 around the 1.5^{o}C and 2^{o}C ?

This study applied continuous time series for identification of drought duration, intensity and severity. From the climate model projections, we noticed that inter-annual variation of global mean air temperature is common and its magnitude differs with different climate models. To account for it, we followed King et al. (*2017*), in which the 1.5^{o}C (*2^{o}C*) world was defined as all years in the 2006-2100 scenario simulations when average temperatures are between 1.3 - 1.7^{o}C (*1.8 - 2.2^{o}C*) warmer than the pre-industrial levels.

In response, we explained the rational of using +/- 0.2 in Line 158-170.

Reference:

King, A.D., Karoly, D.J., and Henley, B.J.: Australian climate extremes at 1.5^{o}C and 2^{o}C of global warming, Nat. Clim. Change, 7, 412-416, doi:10.1038/nclimate3296, 2017.

Line 207: Can you define the used threshold to define the drought duration/ intensity?

We added the used threshold (*PDSI< -1*) for defining the drought duration/intensity/ severity in the revised manuscript. Thank you.

Line 216: That is better to describe a little more the SSP1 scenario for the evolution of the rural/urban people. Your results explain the different trends but we don't know the evolution of the population.
Good point. In response, we added more descriptions about the evolution of population under the SSP1 scenario as follows (Line 248-254 in the latest clean version),

"...In this pathway, the world population would peak at around 2050s and then decline (van Vuuren et al., 2017). The environmental friendly living arrangements and human settlement design in this scenario would lead to fast urbanization in all countries. More in-migrants from rural areas would be attracted to cities due to more adequate infrastructure, employment opportunities and convenient services for their residents (Cuaresma, 2012). The world urban population would gradually increase while rural population would correspondingly decline in the future under SSP1 scenario...."

Line 336: I suggest putting this paragraph before the SSP1 results. I think that is more logical to determine the role of the climate on the population exposure with a current population and after you add the role of the demographic trend.
Done. Thank you.

Technical notes
Line 87: (PDSI) in place of, PDSI,
Line 236: (more drought-prone)?
Line 280: a "." To delete
Done. Thank you.

Response to review comments – RC2:

This paper assesses changes in drought risk (and human population exposure to these risks) at 1.5 and 2 degree thresholds drawn from 11 CMIP5 models and the RCP 4.5 and 8.5 scenarios. Unsurprisingly, they find less risk/exposure at 1.5, though the abstract is missing important details of their results (where is mitigatiodn most important for reducing risks?). I think this study has some potential merit, but I have some significant concerns and critiques that I would like to see addressed before I recommend publication.

Thank you. In the revised manuscript, each of comments/suggestions has been carefully addressed (*please find the point to point response below*). In the acknowledgement section, we added: "*We thank the Editor (Michel Crucifix), Dimitri Defrance and an anonymous reviewer for their helpful comments*". (*Line 452-453 in the latest clean version*).

1) The authors evaluate drought using one specific drought index: PDSI. This is generally fine, but there are some issues regarding how this index is used by the authors. First, despite the title of the original Palmer paper, PDSI is an indicator of agricultural drought risk because it emulates soil moisture availability. Meteorological drought refers specifically to deficits in precipitation. The language in the paper, and the title, should be adjusted accordingly.

We accept the criticism.

In response, we replaced "*meteorological drought*" with "*drought*" in the title and the main text and adjusted the language (*Line 176-179*) to reflect the meaning and implication of PDSI as an indicator of drought risk throughout the manuscript. Thank you.

Second, it is unclear what time period the authors used for the PDSI calibration (i.e., the CAFEC). Typically, one would use some common historical baseline across models so that future changes can be interpreted relative to historical variability. For this particular study, I would recommend using 1850-2000. Doing it this way would thus not require any differencing between future and historical periods, since the PDSI for the future would implicitly reflect drought changes relative to the historical period.

We could have explained the calculation of PDSI more clearly in the original version of this manuscript. The parameters (i.e., *duration factor*) in PDSI model were actually calibrated during the period of 1850-2000 in this study.

In response, we clarified this PDSI calibration and calculation in Section 2.3 (*Line 195-196*). Thank you.

Finally, because of the inherent memory and persistence embedded within the PDSI calculation, this index is much better for picking up long-term and seasonal-scale droughts, and is less appropriate for shorter term (e.g., 1-month) events. For

example, the severe and by some indicators record breaking 2012 drought in the Central Plains of the United States only shows up modestly in PDSI, primarily because this drought intensified quite quickly. For this study, where the authors are interested in month to month changes in drought intensity/persistence/etc, it would be better for the authors to use the Z-index that comes out of the PDSI calculation.
We agree that the PDSI was criticized for its inability to depict droughts on time scales shorter than 12 month when monthly PDSI values were used (*by A.G. Dai, link*: https://climatedataguide.ucar.edu/climate-data/palmer-drought-severity-index-pdsi). However, the purpose of this study is to examine the changes in PDSI-detected drought characteristics (*i.e., monthly-averaged PDSI, mean drought duration, intensity and severity*) between the 1.5/2 degree warmer world and the baseline period. This time-scale related issue is not the focus of this study. Whilst Z-index could assist short-term drought identification, we are not aware of standardized method(s) from existing literature which could help defining drought duration, intensity and severity. By contrast, the PDSI method appears to be a more compelling method in current study.

2) Given the relative coarseness of the CMIP5 models, I think interpolation of the results to 0.5 degree spatial resolution is not appropriate. A 2 degree common grid would be better, and would avoid effectively making up data at the much finer resolution.
In this study, we first calculated the global PDSI and related drought characteristics (*drought duration, intensity and severity*) using GCM-outputs with their original spatial resolution (*the results were thus not affected by interpolation in this step*). The obtained results were then rescaled to a common spatial resolution of $0.5^o \times 0.5^o$ using the bilinear interpolation, in order to (1) show the results with a finer resolution uniformly and (2) accommodate their spatial resolution to that of SSP1 population ($0.5^o \times 0.5^o$). The original resolution of SSP1 population is 0.125 degree. We thus use a 0.5 degree resolution to avoid effectively making up data of the finer resolution in SSP1 data.

In the revised manuscript (*Line 225-231*), we clarified the justification of spatial resolution used in interpolation as follows, to make them more clear and understandable.

"…*It should be noted that the global PDSI and related drought characteristics were first calculated using GCM-outputs with their original spatial resolution. The obtained results were then rescaled to a common spatial resolution of $0.5^o \times 0.5^o$ using the bilinear interpolation, in order to show them with a finer resolution uniformly and accommodate their spatial resolution to that of SSP1 population ($0.5^o \times 0.5^o$). The original resolution of SSP1 population is 0.125 degree. We thus use a 0.5 degree resolution to avoid effectively making up data of the finer resolution in SSP1 data*..."

3) The population analysis in this study is a bit convoluted. For example, the RCP

scenarios use different populations trajectories (I believe), and since you are picking somewhat arbitrary periods that just match desired warming, there will be little consistency in population structure across either the scenarios or warming targets in this analysis (see Figure 1). Since the 1.5 and 2 degree targets are stabilization scenarios, which would theoretically hold out through the end of the 21st century, I think the authors should remove all the population analyses except for the SSP1 2100 analysis (Figure 4). I would also ask the authors to turn Table 4 into one or more figures, since it is difficult for the reader to synthesize such a large table of numbers.
Excellent idea.

In response, we kept the results of SSP1 2100 (*SSP1 2100 population for +1.5 and +2 degree warmer scenarios, SSP1 2000 population for the baseline peri*od) and turned them into three figures (*Figures 11-13*). We removed the old Table 3-4 and Figure 11-13 from the original version of this manuscript. We updated the Method, Results, Conclusion, Abstract sections accordingly. Thank you.

4) For the analyses, how many datapoints (presumably months) are included in each warming scenario?
For the 1.5^{o}C warmer world, there are (12+19)*12=372 data-points (*12 years of 2027-2038 under the RCP4.5 scenario and 19 years of 2029-2047 under the RCP8.5 scenario*) included in the analyses. For the 2^{o}C warmer world, there are totally (29+12)*12=492 data-points (*29 years of 2053-2081 under the RCP4.5 scenario and 12 years of 2042-2053 under the RCP8.5 scenario*) included in the analyses.

In response, we added details of this information in Section 2.2 (*Line 169-170*) of the revised manuscript as follows,

"…In the 1.5^{o}C and 2^{o}C warmer worlds, we get 372 and 492 monthly data-points, respectively.…"

What are the units for drought duration (Figure 5), drought intensity (Figure 7), and severity (Figure 9)? Please add this information to the figure captions.
The unit of drought duration is "*months*" in this study. Drought intensity and severity are two dimensionless variables.

In response, we added this information to both the figure captions and the main text of the revised manuscript (*Line 219-223*). Thank you.

Was significance/robustness/consistency only assessed in terms of agreement across the multi-model ensemble (right columns in the aforementioned figures)? If so, what was the threshold used by the authors to determine whether a given change was sufficiently robust?
In this study, we performed significance/robustness/consistency analyses in different ways. We first quantified the robustness of the results among climate models using

model consistency (*the right panels in Figures 3, 5, 7 and 9*) and boxplots (*Figures 4, 6, 8 and 10*). We then characterized different impacts of severe droughts on population at continental scales using the multi-model ensemble mean and the corresponding uncertainty among climate models in Figures 11-13. For each case, we did not give a fixed threshold to determine whether a given change was sufficiently robust. However, we gave a range of model consistency (from 6/11 to 11/11) to show the results from non-robust (i.e., <6/11), less-robust, median-robust to sufficiently robust (i.e., 11/11). For example, in the right panel of Figure 3, the robustness of projections increases with higher model consistency and vice-versa.

In response, we revised Lines 388-402 to explain the robustness of these results.

5) What is causing the changes in drought risk in these simulations? Declines in precipitation or increases in evaporative demand from warming? Since PDSI is an offline calculation, you can recalculate this index using detrended temperature/ precipitation to tease this out. This would be a valuable addition.
Whilst it is possible to perform attribution study, we have concern that it would shift away from the main focus of current study (*assessing drought risk and its related population impacts under +1.5^o and +2.0^o warmer worlds*) and our target audience (*i.e., international policy-makers*). There are currently many studies focusing on the changes in drought risk and its attribution (*i.e., air temperature, precipitation and potential evaporation*) conducted at both global and regional scales and for both historical and future periods (*Cook et al., 2014; Ficklin et al., 2015; McCabe and Wolock, 2015; Li et al., 2017*). It is an interesting idea worth deep investigation in a separate study, but it is obviously beyond the scope of the current study.

In response, we discussed the plausible future studies related to the review's interesting idea in Line 437-440 as follows,

"…Future studies on understanding the causes of changes in global and regional droughts (e.g., changing pattern/duration of precipitation and evaporative demand) with respect to these warming targets should assist drought risk adaptation and mitigation planning..."

Reference:

Li, Z., Chen, Y.N., Fang, G.H., Li, Y.P.: Multivariate assessment and attribution of drought in Central Asia, Sci. Rep., 7, 1316, 2017.

McCabe, G.J., Wolock, D.M.: Variability and trend in global drought, Earth and Space Science 2, 223-228, 2015.

Ficklin, D.L., Maxwell, J.T., Letsinger, S.L., Gholizadeh, H.: A climate deconstruction of recent drought trends in the United States, Environ. Res. Lett. 10, 044009.

Cook, B.I., Smerdon, J.E., Seager, R., Coats, S.: Global warming and 21st century drying. Clim. Dyn. 43(9-10), 2607-2627, 2014.

Global ~~meteorological~~ drought and severe drought affected population in 1.5^{o}C and 2^{o}C warmer worlds

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Pre-submit to: Earth System Dynamics (*Special issue: Earth System at a 1.5^{o}C warming world*)

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Abstract. ~~In Paris Agreement of 2015,~~The 2015 Paris Agreement proposed a more ambitious climate change mitigation target, on limiting the global warming at 1.5°C instead of 2°C above pre-industrial levels~~, has been proposed~~. Scientific investigations on environmental risks associated with these warming targets ~~investigations~~ are necessary to inform climate policymaking ~~to investigate environmental risks associated with these warming targets~~. Based on the CMIP5 (the fifth Coupled Model Intercomparison Project) climate models, we present~~This study is~~ the first risk-based assessment of changes in global ~~meteorological~~ drought and the impact of severe drought on population at 1.5°C and 2°C additional warming conditions ~~using the CMIP5 (the fifth Coupled Model Intercomparison Project) climate models~~. Our results highlight the risk of ~~meteorological~~ drought at the globe (drought duration would increase from 2.9 to 3.1~3.2 months) and in several hotspot regions such as Amazon, Northeastern Brazil, South Africa and Central Europe at both 1.5 $^{\circ}$C and 2 $^{\circ}$C global warming relative to the historical period. Correspondingly, more total and urban ~~people~~ population would be exposed to severe droughts at the globe (+132.5±216.2 million and +194.5±276.5 million total population, +350.2±158.8 million and +410.7±213.5 million urban population in~~for~~ 1.5 $^{\circ}$C and 2 $^{\circ}$C warmer ~~scenarios~~worlds) and some ~~in many~~ regions (i.e., ~~total and urban population in~~ East Africa, West Africa and South Asia~~East Asia, Southeast Asia, Central Europe~~). ~~Meanwhile, l~~Less rural population would be exposed to severe drought at the globe~~all over the world~~ under both climate warming and population growth (especially the urbanization-induced population migration) ~~and rural population in Central Asia, South Africa and South Asia.~~ ~~).~~ By keeping global~~the~~ warming at 1.5°C above the pre-industrial levels instead of 2°C, ~~the risks of meteorological~~ drought risks would decrease (i.e., less drought duration, drought intensity and drought severity but relatively more

frequent severe drought) and the affected total~~ and~~ , urban and rural population would ~~all~~ decrease~~ (the exposed rural population would increase in most regions) ~~ at the globe and in most regions~~ global and sub-continental scales~~. Whilst challenging for ~~the rural areas~~both East Africa and South Asia, the benefits of limiting warming to below 1.5°C in terms of global drought risk and impact reduction are significant.~~ for reducing the risks and societal impacts of global meteorological drought.~~

1 Introduction

Drought could bring~~is a major natural hazard which could lead to~~ adverse ~~impacts~~ consequences on water supplies, food productions and the environment (Wang et al., 2011; Sheffield et al., 2012). Because of these serious consequences, ~~the occurrence of~~ severe droughts in the recent past ha~~s~~ves gained wide attentions, these include the Millennium drought in ~~s~~Southeast Australia (van Dijk et al., 2013; Kiem et al., 2016), the once-in-a-century droughts in ~~s~~Southwest China (Qiu, 2010, Zuo et al., 2015), the Horn of Africa drought (Masih et al., 2014; Lyon, 2014) and the most recent~~–~~ California drought (Aghakouchak et al., 2015; Cheng et al., 2016). In the context of climate change, drought risks (i.e., drought duration and intensity) are likely to increase in many historical drought-prone regions with global warming (Dai et al., 2012; Fu and Feng, 2014; Kelley et al., 2015; Ault et al., 2016). A better understanding of changes in global drought characteristics and their socioeconomic impacts in the 21st century should feed into long-term climate adaptation and mitigation plans.

The United Nations Framework Convention on Climate Change (UNFCCC) agreed to establish a long-term temperature goal for climate projection of "*pursue efforts to limit the temperature increase to 1.5^{o}C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*" (UNFCCC Conference of the Parties, 2015) in the 2015 Paris Agreement, and invited the Intergovernmental Panel on Climate Change (IPCC) to announce a special report "*On the impacts of global warming of 1.5^{o}C above pre-industrial levels and related greenhouse gas emission pathways*" in 2018 (Mitchell et al., 2016). Regardless of the socio-economic and political achievability of this goals (Sanderson et al., 2017), there is a paucity of scientific knowledge about the relative risks (i.e., drought risks and their potential impacts) associated with the implications of 1.5^{o}C and/or 2^{o}C warming, this naturally attracted contributions from scientific community (Hulme 2016, Schleussner et al., 2016, Peters 2016, King et al., 2017).

To target on the impact assessments of 1.5^{o}C and/or 2^{o}C warming, there are currently several approaches (James et al., 2017). ~~For example, (1)~~One way is to enable impact assessments at near-equilibrium climate of 1.5^{o}C and/or 2^{o}C warmer worlds designed specifically using a set of ensemble simulations produced by~~with~~ a coupled climate model (i.e., Community Earth System Model, CESM) (Sanderson et al., 2017; Wang et al., 2017). Although similar results of drought response to warming were obtained as that conducted by Coupled Model Intercomparison Project-style experiments (i.e., CMIP5, Taylor et al., 2012), the structural uncertainty and robustness of change in droughts among different climate models cannot be fully evaluated in this kind of single-model study (Lehner et al., 2017). ~~(2)~~A second approach extends the former idea to multiple climate models. For instance, ~~T~~the HAPPI (Half a degree Additional warming, Projections, Prognosis and Impacts) model intercomparison project provided a new assessment framework and a dataset with experiment design target explicitly to 1.5°C and 2°C above the pre-industrial levels (Mitchell et al., 2017). However, the analysis/calculation of ~~meteorological~~ drought characteristics ~~needs data~~needs data ~~with longer duration~~~~for~~with long-term period (typically >20 consecutive years, McKee et al., 1993), the ten-year period HAPPI dataset (i.e., 2005-2016 for the historical period and 2105-2116 for the 1.5°C and 2°C warmer worlds) is relatively short (consecutive samples are too short for calculating a drought index, i.e., Palmer drought severity index~~, ~~ (PDSI), Palmer, 1965) for an index-based ~~meteorological~~ drought assessment. ~~(3)~~A third approach utilizes the ~~O~~outputs of~~from~~ CMIP5 climate models under the RCP2.6 scenarios ~~were also applied~~ for this kind of "risk assessment-style" studies, but only a handful of General Circulation Models (GCMs) simulations end up showing 1.5°C global warming by end of the 21^{st} century. Alternatively, transient simulations from multiple CMIP5 GCMs at higher greenhouse emissions (i.e., the RCP4.5 and RCP8.5) (Schleussner et al., 2016; King et al., 2017) could be analyzed in order to evaluate the potential risks of ~~meteorological~~ drought under different warming targets, albeit the long-duration drought years might be underestimated due to insufficient sampling of extended drought events (Lehner et al., 2017).

Here, we quantify the changes in global and sub-continental ~~meteorological~~ drought characteristics (i.e., drought duration, intensity and severity) at 1.5°C and 2°C above the pre-industrial levels and find out whether there are significant differences between them. We perform this analysis using a drought index-PDSI forced by the~~a suite of~~ latest CMIP5 GCMs. To evaluate the societal impacts, we incorporate the Shared Socioeconomic Pathway 1 (SSP1) spatial explicit global population scenario and examine the exposure of population (including rural, urban and total population) to severe droughts~~ events~~. This paper is organized as follows: Section 2 introduces the CMIP5 GCMs output and SSP1 population data applied in this study. ~~The definition of~~ We define the baseline~~ period~~, 1.5°C and 2°C warmer world;~~s,~~ and describe the calculation of PDSI-based drought characteristics and population exposure under~~exposed to~~ severe droughts ~~are also described~~ in this section. Section 3 shows the results (i.e., hotspots and risks) of changes in drought characteristics and the impacts of severe drought on people under these warming targets. We perform ~~D~~detailed discussions~~ are performed~~ in Section 4 and conclude our findings ~~, followed by the conclusions~~ in Section 5.

2 Material and Methods

2.1 Data

In this study, we use the CMIP5 GCMs output (including the monthly outputs of surface mean air temperature, surface minimum air temperature, surface maximum air temperature, air pressure, precipitation, relatively humidity, surface downwelling longwave flux, surface downwelling shortwave flux, surface upwelling longwave flux and surface upwelling shortwave flux as well as the daily outputs of surface zonal velocity component ($uwnd$) and meridional velocity component ($vwnd$)) ~~under two Representative Concentration Pathways (RCP4.5 and RCP8.5)~~ archived at the Earth System Grid Federation (ESGF) Node at the German Climate Computing Center-DKRZ (https://esgf-data.dkrz.de/projects/esgf-dkrz/) over the period 1850-2100. In the

CMIP5 archive, the monthly $uwnd$ and $vwnd$ were computed as the means of their daily values with the plus-minus sign, the calculated wind speed from the monthly $uwnd$ and $vwnd$ would be equal to or, in most cases, less than that computed from the daily values (Liu and Sun, 2016). To get the monthly wind speed, we average the daily values ($\sqrt{uwnd^2 + vwnd^2}$) over a month.

Eleven GCMs (see details of these GCMs in Table 1) under two Representative Concentration Pathways (an intermediate and a substantially rising pathway, RCP4.5 and RCP8.5) were finally selected based on the availability of all input variables to compute the PDSIRecent studies have confirmed that the impacts of similar global mean surface temperature (i.e., +1.5°C and +2°C warmer worlds) among the Representative Concentration Pathways (RCPs) are quite similar, implying that the global and regional responses to temperature and are independent of the RCPs (Hu et al., 2017; King et al., 2017). Following this idea, we settled at using 11 CMIP5 models which satisfied the data requirement of PDSI calculation (see paragraph above) under RCP4.5 and RCP8.5. Following Wang et al. (2017) and King et al. (2017), we use the ensemble mean of these CMIP5 models and climate scenarios (RCP4.5, RCP8.5) to composite the warming scenarios (+1.5°C and +2°C warmer worlds).Recent studies have confirmed that the impacts of similar global mean surface temperature (i.e., +1.5oC and +2oC worlds) among the Representative Concentration Pathways (RCPs) are quite similar, implying that the global and regional responses to temperature and are independent of the RCPs (Hu et al., 2017; King et al., 2017). Following this idea, we finally settled at using 11 CMIP5 models which satisfied the data requirement of PDSI calculation (see paragraph above) under RCP4.5 and RCP8.5. Following Wang et al. (2017) and

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King et al. (2017), we use the ensemble mean of these CMIP5 models and climate scenarios (RCP4.5, RCP8.5) to composite the warming scenarios (+1.5oC and +2oC worlds).. Some studies (King et al., 2017; Hu et al., 2017) have found that the global and regional responses (i.e., warming/precipitation patterns) to varied warming scenarios (i.e., 1.5oC and 2oC) showed little dependences on RCP scenarios (RCP2.6, RCP6, RCP4.5 and RCP8.5). Therefore, in this study, following the approaches adopted by Wang et al. (2017) and King et al. (2017), we only chose two RCP scenarios to composite the warming scenarios of 1.5oC and 2oC using the ensemble mean of multiple climate models and emission scenarios. Based on data availability, we select 11 GCMs to perform the analysis (see details of these GCMs in Table 1). In the CMIP5 archive, the monthly uwnd and vwnd were computed as the means of their daily values with the plus-minus sign, the calculated wind speed from the monthly uwnd and vwnd would be equal to or, in most cases, less than that computed from the daily values (Liu and Sun, 2016). To get the monthly wind speed, we average the daily values ($\sqrt{uwnd^2+vwnd^2}$) over a month. We rescale all data to a common spatial resolution of 0.5°×0.5° using the bilinear interpolation.

<Table 1, here, thanks>

To consider the people affected by severe drought events, we use the spatial explicit global population scenarios developed by researchers from the Integrated Assessment Modeling (IAM) group of National Center for Atmospheric Research (NCAR) and the City University of New York Institute for Demographic Research (Jones and O'Neil, 2016). They included the gridded population data for the baseline year (2000) and for the period of 2010-2100 in ten-year steps at a spatial resolution of 0.125 degree, which are consistent with the new Shared Socioeconomic Pathways (SSPs). We apply the population data of the SSP1 scenario, which describes a future

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pathway with sustainable development and low challenges for adaptation and mitigation. We upscale this product to a spatial resolution of 0.5° ×0.5°. For the global and sub-continental scales analysis, we use the global land mass between 66°N and 66°S (Fischer et al., 2013; Schleussner et al., 2016) and 26 sub-continental regions (as used in IPCC, 2012, see Table 2 for details).

<Table 2, here, thanks>

2.2 Definition of a baseline, 1.5°C and 2°C warmer worlds

To define a baseline, 1.5°C and 2°C warmer worlds, we first calculate the global mean surface air temperature (GMT) for each climate model and emission scenario over the period 1850-2100. We weigh~~note that~~ the surface air temperature field ~~need be weighted~~ by the square root of cosine (latitude) to consider the dependence of grid density on latitude (Liu et al., 2016). ~~The~~ We compute and smooth the ~~M~~multi-model Ensemble Mean (MEM) GMT ~~were computed and smoothed~~ using a 20-year moving average filter for the RCP4.5 and RCP8.5 ~~scenarios~~, respectively. This study applied continuous time series for identification of drought duration, intensity and severity. From the climate model projections, we noticed that inter-annual variation of global mean air temperature is common and its magnitude differs with different climate models. To account for it, following ~~Following the method in~~ Wang et al. (2017), we first select a baseline period of 1986-2005 for which~~when~~ the observed GMT was about 0.6°C warmer (the MEM GMT was 0.4~0.8 °C warmer during this period in 11 climate models used) than the pre-industrial levels (1850-1900, IPCC, 2013). This is also a common reference period for climate impact assessment (e.g., Schleussner et al., 2016). Next, for each ~~emiassion~~emission scenario (RCP4.5 or RCP8.5), we define the periods (Figure 1) during which the 20-year smoothed GMT increase by 1.3~1.7 °C (2027-2038 under the RCP4.5 and 2029-2047 under the RCP 8.5) and by 1.8~2.2 °C

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(2053-2081 under the RCP4.5 and 2042-2053 under the RCP 8.5) above the pre-industrial period as the 1.5°C and 2°C warmering worlds, respectively (as in King et al., 2017). To reduce the projection uncertainty inherited from different emission scenarios, we combine (by averagingaverage) the results of drought characteristics and population exposures calculated forduring different selected periods under the RCP4.5 and RCP8.5, to represent the ensemble means -meteorological of drought risk at 1.5°C or 2°C warmer worlds. In the 1.5°C and 2°C warmer worlds, we get 372 and 492 monthly data-points, respectively.It finally results in totally 372 (31 years) and 492 (41 years) data points (months) for the 1.5°C and 2°C warming scenarios in the following analysis.

<Figure 1, here, thanks>

2.3 Characterize meteorological global drought using PDSI

To quantify the changes in drought characteristics, we adopt the most widely used Palmer Drought SeverityPDSI index (PDSI), which describes the balance between water supply (precipitation) and atmospheric evaporative demand (required "precipitation" estimated under climatically appropriate for existing conditions, CAFEC) at the monthly scale (Wells et al., 2004; Zhang et al., 2016). ItFor a multiyear time series, this index is commonly applied as an indication for identification ofpopularly used in quantifying a meteorological drought; and to a lesser extent, a hydrological droughts (especially the former) (Heim Jr., 2002; Zargar et al., 2011; Hao et al., 2018). Briefly, iIt incorporates antecedent precipitation, potential evaporation and the local Available Water Content (AWC, links: https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=548) of the soil in the hydrological accounting system. It measures the cumulative departure relative to the local mean conditions in atmospheric moisture supply and demand on land surface. In the PDSI model, five surface water fluxes, namely, precipitation (*P*), recharge to soil (*R*), actual evapotranspiration (*E*), runoff (*RO*) and water loss to the soil layers (*L*); and their potential values $\hat{P}$, *PR*, *PE*, *PRO* and *PL* are considered. All values in the model can be computed under CAFEC values using the precipitation, potential evaporation and AWC inputs. For example, the CAFEC precipitation ($\hat{P}$) is defined as (Dai et al., 2011),

$$\hat{P} = \frac{\overline{E_\iota}}{\overline{PE_\iota}} PE + \frac{\overline{R_\iota}}{\overline{PR_\iota}} PR + \frac{\overline{RO_\iota}}{\overline{PRO_\iota}} PRO - \frac{\overline{L_\iota}}{\overline{PL_\iota}} PL, \quad (1)$$

In Equation 1, ~~Here~~ the over bar indicates averaging of a parameter over the calibration period. The moisture anomaly index (*Z* index) is derived as the product of the monthly moisture departure ($P - \hat{P}$) and a climate characteristics coefficient *K*. The *Z* index is then applied to calculate the PDSI value for time $t(X_t)$:

$$X_t = pX_{t-1} + qZ_t = 0.897X_{t-1} + Z_t/3 \quad (2)$$

Where X_{t-1} is the PDSI of the previous month, and p and q are duration factors. The calculated PDSI ranges -10 (dry) to 10 (wet). The parameters (i.e., the duration factor) in PDSI model are~~were~~ calibrated ~~using~~using the period ~~of~~ 1850-2000 (see Section 2.2).

~~Details of PDSI are available in Palmer (1965) and Wells et al. (2004).~~

As part of the PDSI ~~-~~calculation, we quantify~~calculate~~ the potential evaporation (PET) using the Food and Agricultural Organization (FAO) Penman-Monteith equation (Allen et al., 1998),

$$PET = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2 e_s(1 - \frac{Rh}{100})}{\Delta + \gamma(1 + 0.34U_2)} \quad (3)$$

where Δ is the slope of the vapor pressure curve, U_2 is the wind speed at 2 m height, G is the soil heat flux, Rh is the relative humidity, γ is the psychometric constant, e_s is the saturation vapor pressure at a given air temperature (T). R_n is the net radiation which can be calculated using the surface downwelling/upwelling shortwave and longwave radiations. We estimate all other parameters in the FAO Penman-Monteith equation using the GCM outputs through the standard algorithm as per recommended by the FAO (Allen et al., 1998). In this study, we perform this calculation for each GCM over the period 1850-2100 using the tool for calculating the ~~Palmer drought indices~~PDSI (the original MATLAB codes were modified for this case) developed by Jacobi et al. (2013).

Based on the calculated global PDSI, we derive the drought characteristics (i.e., drought duration, drought intensity and drought severity) using the run theory for the baseline, 1.5°C and 2°C warmer~~ing~~ worlds, respectively. Briefly, the concept of "run theory" is proposed by Yevjevich and Ingenieur (1967). The run characterizes the statistical properties of sequences in both time and space. It is useful for defining drought in an objective manner. In the run theory, a "run" represents a portion of time series X_i, where all values are either below or above a specified threshold (we set the threshold PDSI < -1 in this study) (Ayantobo et al., 2017). We define a "run" with values continuously stay below that threshold (i.e., negative run) as a drought event, which generally includes these characteristics: drought duration, drought intensity and drought severity (see Figure 2 for better illustration). We define the drought duration (months in this study) as a period (years/months/weeks) which PDSI stays below a specific threshold (PDSI < -1). Drought severity (dimensionless) indicates a cumulative deficiency of a drought event below the threshold (PDSI < -1), while drought intensity (dimensionless) is the average value of a drought event below the this threshold (Mishra and Singh, 2010). For each GCM, we calculate the medians of drought duration, drought intensity and drought severity at each grid-cell across all drought events for each selected period (i.e., the baseline, 1.5°C and 2°C warmering worlds). It should be noted that the global PDSI and related drought characteristics were first calculated using GCM-outputs with their original spatial resolution. The obtained results were then rescaled to a common spatial resolution of 0.5° ×0.5° using the bilinear interpolation, in order to show them with a finer resolution uniformly and accommodate their spatial resolution to that of SSP1 population (0.5° ×0.5°). The original resolution of SSP1 population is 0.125 degree. We thus use a 0.5 degree resolution to avoid effectively making up data of the finer resolution in SSP1 data. We generalize synthesize the results by evaluating the ensemble mean and model consistency/inter-model variance across all climate models. We notewarmer Previous studies have demonstrated thatOalso which would be difficult to maintainusing. For simplicity

<Figure 2, here, thanks>

2.4 Calculation of population exposure underto severe droughts

Following Wells et al. (2014), we assume that a severe drought event occurs when monthly PDSI < -3, we assume a severe drought event took place. If a severe drought occurredoccurs for at least a month in a year, we would take that year –as a severe drought year. For each GCM per period (i.e., the baseline, 1.5°C and 2°C warmering worlds), we quantify the population (including urban, rural and all population) affected by severe drought per grid-cell as (population × annual frequency of severe drought). We first compute the affected population for the baseline period (1985-2005) using the SSP1 base year (2000). Since the 1.5°C and 2°C targets are stabilization scenarios, which would theoretically hold out through the end of the 21st century.

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We repeat this estimation using the constant SSP1 population data in 2100 for the 1.5°C and 2°C warming worlds, which is consistent with the original proposal of Paris Agreement on stabilizing global warming for the specified targets by end of the 21st century. ~~using the SSP1 data (see Section 2.1). For example, we used the SSP1 base year (2000), 2030 (centered year in the 1.5°C warming period: 2027-2047 for both RCP scenarios) and 2060 (centered year in the 2°C warming period: 2042-2081 for both RCP scenarios) population data for the baseline period (1985-2005), 1.5°C and 2°C warming worlds, respectively. To evaluate the climate impact on society without population growth, we estimate the population exposure using the SSP1 data of the base year (2000). We repeat this estimation using the constant SSP1 population data in 2100, which is consistent with the original proposal of Paris Agreement on stabilizing global warming for the specified targets by end of the 21st century.~~ We used SSP1 scenario because it describes the storyline of a green growth paradigm with sustainable development and low challenges for adaptation and mitigation~~–~~ (Jones and O'Niell, 2016). The ~~+~~1.5°C and ~~+~~2°C warmer worlds clearly fit in this description and thus considered under the 2015 Paris Agreement ~~2015~~ (UNFCCC Conference of the Parties 2015; O'Niell et al., 2016). In this pathway, the world population would~~will~~ peak at around 2050s and then decline (van Vuuren et al., 2017). The environmental~~ly~~ friendly living arrangements and human settlement design in this scenario ~~leads~~would lead to fast urbanization in all countries. More in-migrants from rural areas would be~~are~~ attracted to cities due to more adequate infrastructure, employment opportunities and convenient services for their residents (Cuaresma, 2012). The world urban population would~~will~~ gradually increase while rural population would~~will~~ correspondingly decline in the future under SSP1 scenario.

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3 Results

3.1 Changes in PDSI and drought characteristics

We present the changes in multi-model ensemble mean PDSI from the baseline period (1986-2005) to each of the 1.5°C and 2°C scenarios and model consistency in Figure 3. For the 1.5°C warmer world, the PDSI would decrease (more drought-prone) with relatively higher model consistency (6~11 models in totally 11 climate models) in some regions, for example, Amazon (0.7±0.8 -> -0.1±0.2), Northeastern Brazil (0.5±0.6 -> -0.1±0.3), Southern Europe and Mediterranean (0.4±0.6 -> -0.3±0.2), Central America and Mexico (0.2±0.4 -> -0.2±0.1), Central Europe (0.3±1.0 -> -0.1±0.4) as well as Southern Africa (0.5±0.5 -> -0.3±0.2); slightly increase (less drought-prone) in Alaska/Northwest Canada (-0.01±0.5 -> -0.3±0.2) and North Asia (-0.1±1.0 -> -0.2±0.2) but with relatively low model consistency. The geographic pattern of changes in PDSI for the 2°C warmer world~~scenario~~ is quite similar to that of 1.5°C warmer world, but the magnitude of change would intensify (in both direction) East Canada, Greenland, Iceland (-0.3±0.2-> -0.4±0.2), East Africa (-0.5±0.2-> -0.3±0.2), Northern Europe (-0.3±0.3-> -0.2±0.3), East Asia (-0.3±0.1-> -0.2±0.4), South Asia (-1.0±1.2-> -0.8±0.3) and West Africa (-0.3±0.2-> -0.3±0.3). When global warming is capped~~kept~~ at 1.5°C instead of 2°C above the pre-industrial levels, the PDSI value would elevate~~be larger~~ at the globe (66°S-66°S, -0.4±0.2-> -0.3±0.2) and most regions (Alaska/Northwest Canada, East Africa, West Africa, Tibetan Plateau, North Asia, East Asia, South Asia and Southeast Asia) (Figure 4).

<Figure 3, here, thanks>

<Figure 4, here, thanks>

We analyze the changes in ~~meteorological~~ drought characteristics such as its duration, ~~-~~severity and ~~-~~intensity in~~under the~~ 1.5^{o}C and 2^{o}C warmer worlds~~warming conditions~~. In terms of the drought duration (Figures 5 ~~and Figure~~ -6), we find robust large-scale features. For example, the drought duration would generally increase at the globe (2.9±0.5 -> 3.1±0.4 months and 2.9±0.5 -> 3.2±0.5 months from the baseline period to the 1.5^{o}C and 2^{o}C scenarios) and most regions (especially for Amazon, Sahara, Northeastern Brazil and North Australia) except for North Asia (2.7±0.6 -> 2.6±0.5 months and 2.7±0.6 -> 2.5±0.4 months) in both~~under both the 1.5^{o}C and 2^{o}C warmer~~ worlds. The high model consistency ~~-~~in most regions (i.e., Amazon, Sahara and Northeastern Brazil) for both warming targets~~warming scenarios~~ gives us more confidence on these projections. Relative to the 2^{o}C warmer target, a 1.5^{o}C warming target is more likely to reduce drought duration at both global and regional scales (except for Alaska/Northwest Canada, East Africa, Sahara, North Europe, North Asia, South Asia, Southeast Asia, Tibetan Plateau and West Africa).

<Figure 5, here, thanks>

<Figure 6, here, thanks>

Drought intensity and drought severity are commonly used for quantifying~~, to what extent,~~ the extent of water availability drops significantly below normal conditions in~~for~~ a region. In this study, the drought intensity is projected to increase at the globe (0.9±0.3 -> 1.1±0.3 and 0.9±0.3 -> 1.0±0.2~~-~~ from the baseline period to the 1.5^{o}C and 2^{o}C scenarios) and in most of the regions except for North Asia, Southeast Asia and West Africa in ~~under the~~ 1.5^{o}C and 2^{o}C warmer worlds~~warming scenarios~~ (Figures 7-8). Compare to the 2^{o}C warmer world~~scenario~~, the drought intensity would obviously relievebe relieved at the global and sub- continental scales except for East Canada, Greenland, Iceland (1.0±0.6 -> 0.8±0.5) and West North America (0.9±0.3 -> 0.8±0.2) in the 1.5°C warmer world. In addition, the projected drought severity would also increase in theseboth 1.5°C and 2°C warmer worlds at the globe –(3.0±1.9 -> 4.5±3.0 and 3.0±1.9 -> 3.8±2.0 from the baseline period to the 1.5°C and 2°C warmer worldsscenarios) –and in most regions except for North Asia (1.8±0.6 -> 1.8±0.7 and 1.8±0.6 -> 1.5±0.3) (Figures 9-10). When global warming is maintained at 1.5°C instead of 2°C above the pre-industrial levels, the drought severity would weaken in most regions except for Sahara (3.1±0.9-> 3.5±1.3), North Asia (1.5±0.3 -> 1.8±0.8), Southeast Asia (17.2±20.1 -> 35.8±57.2), and West North America (2.4±1.7 -> 2.5±1.4).. The projected uncertainties are relatively low (6~11 models in totally 11 models) for the changes of each drought characteristic under differentin these warming scenarios all over the world, except for some parts of Alaska/Northwest Canada, East Canada, Greenland, Iceland, West North America, Central North America, East North America, Sahara, West Africa, East Africa and North Asia.

<Figure 7, here, thanks>

<Figure 8, here, thanks>

3.2 Impact of severe drought on population

To understand the societal influences of severe drought, we combine the drought projection with SSP1 population information and estimate the total, urban and rural population affected by severe drought in the baseline period, 1.5°C and 2°C warmer worlds (Figures 11-13) (Figures 11-13). Compare to the baseline period, the frequency of severe drought (PDSI < -3), drought-affected total and urban population would increase in most of the regions inunder the

1.5°C and 2°C ~~warming scenarios~~warmer worlds. ~~To exclude the role of population growth in the former analysis, we also repeat the analysis but this time we keep the population constant in 2000 (Table 4).~~ Globally, we estimate that ~~63.8~~132.5±~~195.9~~216.2 million (~~33.3~~50.2±~~86.6~~158.8 million urban population and ~~30.5~~ 217.7±~~113.6~~79.2 million rural population) and ~~122.4~~194.5±~~249.9~~76.5 million (~~55.4~~410.7±~~101.8~~213.5 million urban population and ~~67.0~~ 216.2±~~150.7~~82.4 million rural population) additional people would be exposed~~be exposed~~ solely to severe droughts in the 1.5°C and 2°C warmer worlds, respectively. The severe drought affected total population would increase under these warming targets in most regions, except for East Asia, North Asia, South Asia, Southeast Asia, Tibetan Plateau and West Coast South America.

<Figure 9, here, thanks>

<Figure 10, here, thanks>

The severe drought affect urban (rural) population would increase (decrease) in all global regions in~~under the~~ 1.5°C and 2°C warmer worlds~~warming scenarios~~. For example, the projections suggest that more urban population would be exposed~~expose~~ to severe drought in Central Europe (10.9±7.7 million), Southern Europe and Mediterranean (14.0±4.6 million), West Africa (65.3±34.1 million), East Asia (16.1±16.0 million), West Asia (16.2±7.4 million) and Southeast Asia (24.4±19.7 million) in ~~the~~ 1.5°C warmer world relative to the baseline period. We also find that the number of affected people would escalate further in these regions in~~under the~~ 2°C warmer world~~warming scenario~~. In terms of the rural population, less people in Central Asia (-4.1±4.7 million and -3.3±4.1 million for the 1.5°C and 2°C warmer worlds), Central North America (-0.5±1.1 million and -0.4±0.9 million), Southern Europe and Mediterranean (-3.6±3.2 million and -2.9±3.8 million), South Africa (-3.3±1.5 million and -2.9±1.8 million), Sahara (-1.0±2.5 million and

-0.9±2.9 million), South Asia (-70.2±29.7 million and -72.9±30.0 million), Tibetan Plateau (-2.3±1.8million and -2.1±1.9 million) and West North America (-1.7±1.0 million and -1.6±1.1 million) would be exposedexpose to the severe drought in the 1.5°C and 2°C warmer worlds relative to the baseline period. The distinct influences of severe drought on urban and rural population are driven by both climate warming and population growth, especially by the urbanization-induced population migration.

<Figure 11, here, thanks>

<Figure 12, here, thanks>

When global warming approaches 1.5°C (instead of 2°C) above the pre-industrial levels, relatively less total, urban and rural population (except for East Africa and South Asia) would be affected despite more frequent severe drought in most regions such as East Asia, Southern Europe and Mediterranean, Central Europe and Amazon. In terms of percentage, about 75% and 50% of total affected population (considers both severe droughts and population growth, including 86% and 88% of the affected urban population as well as 114% and -67% of the affected rural population) are attributable to population growth while others are solely due to climate change impact under the 1.5°C and 2°C warming scenarios, respectively. The climate change driven severe drought affected total, urban and rural population would decrease in East Africa and South Asia but increase (the climate change driven severe drought affected population constitutes >50% of that considering both climate change and population growth) in most regions (for example, North Australia, Southern Europe and Mediterranean, Central Europe, North Europe, West Coast South America, Northeastern Brazil, Central North America and East Asia for total population as well as West North America, Central North America, East North America, Central America and Mexico, Amazon, Northeastern Brazil, West Coast South America, Southeastern South America, Northern Europe, Central Europe, Southern Europe and Mediterranean, West Africa, South Africa, North Asia, Central Asia, Tibetan Plateau, East Asia and Southeast Asia for rural population) under these warming targets.

<Figure 9, here, thanks>

<Figure 10, here, thanks>

Compare to the baseline period, the frequency of severe drought (PDSI < -3), drought-affected total and urban population would increase in most of the regions under the 1.5°C and 2°C warming scenarios.

<Figure 9, here, thanks>

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The projections suggest that more urban population would expose to severe drought in Central Europe (16.4±8.5 million), Southern Europe and Mediterranean (13.3±4.7 million), West Africa (26.7±15.7 million), East Asia (44.3±20.6 million), South Asia (17.7±37.6 million), West Asia (14.9±7.8 million) and Southeast Asia (19.9±17.0 million) in the 1.5°C warmer world relative to the baseline period. We also find that the number of affected people would escalate further in these regions under the 2°C warming scenario (Table 3). In terms of the rural population, more people in Central Asia (2.2±6.4 million and 1.2±3.5 million for the 1.5°C and 2°C warmer worlds), Central North America (0.8±1.7 million and 0.4±1.0 million), Southern Europe and Mediterranean (0.9±3.4 million and 0.3±4.9 million), South Africa (1.9±1.9 million and 0.9±2.6 million), Sahara (0.1±2.5 million and 0.3±3.2 million), South Asia (45.9±52.4 million and -23.1±26.9 million), Tibetan Plateau (0.3±2.7 million and -1.03±2.1 million) and West North America (-1.2±0.9 million and 0.1±0.1 million) would expose to the severe drought in the 1.5°C and 2°C warmer worlds relative to the baseline period (except for the globe, South Asia and Tibetan Plateau under the 2°C warming scenario and West North America under the 1.5°C warming scenario). Overall, the multi-model projected uncertainty of affected population (including total, urban and rural population) is quite small in most regions except for East Asia, South Asia and West Africa.

<Figure 11, here, thanks>

<Figure 12, here, thanks>

When global warming approaches 1.5°C (instead of 2°C) above the pre-industrial levels, relatively less total (except for total population affected in North Asia, East Asia, Southeast Asia and South Asia) and urban population would be affected despite more frequent severe drought. By contrast, the affected rural population would increase in most regions (except for Amazon, East Canada, Greenland, Iceland, North Australia, Northeastern Brazil, Sahara and South Australia/New Zealand). This implies that the benefit of holding global warming at 1.5°C instead of 2°C is apparent to the severe-drought affected total and , urban and rural population in most regions, but challenges remain in the rural areas (especially in South Asia, Southeast Asia, East Africa and West Africa)East Africa and South Asia.

<Figure 13, here, thanks>

<Table 3, here, thanks>

We repeat similar analysis using the constant SSP1 population in 2100 (Figure 4). Relative to the baseline period, we find that 38.6±272.7million (38.7±247.1 million urban population and 0.0±26.1million rural population) and 100.3±323.9 million (99.1±295.9 million urban population and 1.5±28.5 million rural population) additional population would expose to severe droughts in the 1.5°C and 2°C warmer worlds on a global scale. The severe drought affected total, urban and rural population would increase under these warming targets in most regions except for Sahara (total and rural population under 1.5°C warming scenario and rural population under 2°C warming scenario), East Africa, South Asia and West Africa (rural population under 1.5°C warming scenario). Moreover, compare to the 2°C warming target, the severe drought affected total, urban and rural population would decrease in the 1.5°C warmer world in most regions such as East Asia, Southern Europe and Mediterranean, Central Europe and Amazon.

To exclude the role of population growth in the former analysis, we also repeat the analysis but this time we keep the population constant in 2000 (Table 4). Globally, we estimate that 63.8±195.9 million (33.3±86.6 million urban population and 30.5±113.6 million rural population) and 122.4±249.9 million (55.4±101.8 million urban population and 67.0±150.7 million rural population) additional people would be exposed solely to severe droughts in the 1.5°C and 2°C warmer worlds, respectively. In terms of percentage, about 75% and 50% of total affected population (considers both severe droughts and population growth, including 86% and 88% of the affected urban population as well as 114% and -67% of the affected rural population) are attributable to population growth while others are solely due to climate change impact under the 1.5°C and 2°C warming scenarios, respectively. The climate change driven severe drought affected total, urban and rural population would decrease in East Africa and South Asia but increase (the climate change driven severe drought affected population constitutes >50% of that considering both climate change and population growth) in most regions (for example, North Australia, Southern Europe and Mediterranean, Central Europe, North Europe, West Coast South

America, Northeastern Brazil, Central North America and East Asia for total population as well as West North America, Central North America, East North America, Central America and Mexico, Amazon, Northeastern Brazil, West Coast South America, Southeastern South America, Northern Europe, Central Europe, Southern Europe and Mediterranean, West Africa, South Africa, North Asia, Central Asia, Tibetan Plateau, East Asia and Southeast Asia for rural population) under these warming targets.

<Table 4, here, thanks>

4 Discussions

The changes in PDSI, drought duration, intensity and severity with climate warming (i.e., +1.5°C and +2°C warmer worlds) projected in this study is in general agreement with that concluded by IPCC (2013) despite regional variation, although they vary among regions. For example, as revealed in this study, the gradual decline of PDSI (drought-prone) in American Southwest and Central Plains was also projected using an empirical drought reconstruction and soil moisture metrics from 17 state–of-the-art GCMs in the 21st century (Cook et al., 2015). The ascending risk of drought in Sahara, North Australia and South Africa coincided with Huang et al. (2017), which projected that globalthat global drylands would degrade inunder the 2°C warmer worldglobal warming target. Moreover, the increases in drought duration, intensity and severity in Central America, Amazon, South Africa and Mediterranean are in agreement with the extension of dry spell length and less water availability in these regions under the 1.5°C and/or 2°C warming scenarios (Schleussner et al., 2016; Lehner et al., 2017). In addition, we find that the affected population attributes more (50%~75%) to the population growth rather than the climate change driven severe drought in the 1.5°C and 2°C warmer worlds. This numberfigure is greaterhigher than that concluded by Smirnov et al. (2016), maybe due to different study periods, population data, drought index and warming scenarios used.

~~This study illustrates some of the differences in drought characteristics at both global and sub-continental scales that could be expected in a 1.5°C and 2°C warmer worlds. These p~~Projections presented in current study inherited several sources of uncertainty. Firstly, there are considerable uncertainties in the numerical projections from different climate models under varied greenhouse gas emission scenarios, especially on a regional scale (i.e., Sahara, Alaska/Northwest Canada and North Asia). However, the utility of multiple GCMs and emission scenarios should allow us to synthesize~~generalize~~ future projections better than ~~that using~~ single model/scenario analysis (Schleussner et al., 2016; Wang et al., 2017; Lehner et al., 2017). On top of that, we performed uncertainty analysis such as understanding the model consistency (e.g., increase/decrease) and inter-model variance (for magnitude changes). These enable us to characterize regional and global projections which could vary due to different model structure of GCMs and how they behave under different RCP scenarios. Moreover, the global and regional responses (i.e., warming/precipitation patterns) to varied warming scenarios (i.e., 1.5°C and 2°C) showed little dependences on RCP scenarios (King et al., 2017; Hu et al., 2017). Therefore, the uncertainty caused by the choice of RCP scenarios might be small~~may be minor~~. Secondly, there are various ways of picking the 1.5°C or 2°C warming signals (King et al., 2017). ~~In this study, we~~Current study considered both the influences of multi-model and multi-scenario for each warming scenario using the 20-year smoothed multi-model ensemble mean GMT. The selected periods of 1.5°C ~~and/or~~and 2.0°C warmer worlds ~~is~~are close to that of King et al. (2017). Finally, the SSP1 population data and the single drought index used might introduce uncertainties. Despite these sources of uncertainty, these projections are quite robust with high model consistency across most regions.

This analysis evaluated the risk of droughts in terms of how they would change in the future period (1.5^{o}C or 2^{o}C warmer worlds) relative to the baseline period; and the difference between the two warmer worlds. In this perspective, uncertainty arises from climate model bias in between two periods more or less cancels each other. Previous studies demonstrated that bias-corrections do not yield much difference in such circumstance (e.g., Sun et al., 2011; Maraun, 2016). In addition, the methodology here requires the meteorological information with physical meaning (see Section 2.1) that is consistent with the energy balance of the climate model (Equation 3 in Section 2.3), hence existing bias-correction measures (with known weakness in maintaining the physical aspect of bias-corrected output) appears less feasible. (Future innovation which accounts for both statistics and energy balance of climate model output in new bias-correction methodology for handling the high non-linear outcomes should be a subject of scientific interest.) The rationale of using model consistency (Figures 3, 5, 7, 9) as a form of "confidence index" here emerges from the idea that, whilst model validation in historical period is helpful, it does not necessary reveal the ability of each climate model in projection of risk change. Thus this kind of confidence index is informative for synthesizing multi-model projectionsand more general, probably explains why it is still common in many global studies involving multi-model ensembles (e.g., Hirabayashi et al., 2013; Koirala et al., 2014).

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5 Conclusions

Motivated by the 2015 Paris Agreement proposal, Based on the CMIP5 GCMs output, we analyzed the CMIP5 GCM output and presented the first comprehensive assessment of changes in meteorological drought characteristics and the potential impacts of severe drought on populationon population (total, urban and rural) inunder the 1.5°C and 2°C warmer worlds. We found that the risk of meteorological drought would increase (i.e., decrease in PDSI, increase in drought duration, drought intensity and drought severity) globally and most regions (i.e., Amazon, Northeastern Brazil, Central Europe) for inboth 1.5°C and 2°C warmering worldsscenarios relative to the baseline period (1986-2005). However, the amplitudes of change in drought characteristics vary among the regions. Relative to the 2°C warming target, a 1.5°C warming target is more likely to reduce drought risk (less drought duration, drought intensity and drought severity but relatively more frequent severe drought) significantly on both global and regional scales. The high model consistency (6~11 out of 11 GCMs) across most regions (especially Amazon, Sahara and Northeastern Brazil) gives us more confidence on these projections.

Despite the uncertainties inherited from the GCMs and population data used, as well as the definition of the 1.5°C and 2°C periods, we found significant changes of drought characteristics under both warming scenarios and societal impacts of severe drought by limiting temperature target at 1.5 °C instead of 2 °C in several hotspot regions. More total (+132.5±216.2 million+259.3±238.1 million and +194.5±276.5245.8±331.1 million globally) and urban population (+350.2±158.8232.6±124.8 million and +410.7±213.5468.3±228.0 million globally) would be exposed exposed to severe drought in most regions (especially East Asia,Africa, West

Africa and South~~ east~~ Asia~~ and Central Europe~~) in~~for both~~ 1.5 °C and 2 °C warmer worlds~~ing scenarios~~, particularly for the latter case.

Meanwhile, ~~more~~ less rural population (-217.7±79.2~~+26.7±119.0~~ million and -216.2±82.4 ~~-99.3±100.2~~million globally) in, e.g., Central Asia, East Canada, Greenland, Iceland, Central North America, Southern Europe and Mediterranean, North Australia, South Africa, Sahara, South Asia, Tibetan Plateau and West North America would be affected. When global mean temperature increased by 1.5 °C ~~—~~instead of 2 °C above the pre-industrial level, the total~~ (except for the global scale which would increase by ~5.5%) and u~~, urban and rural population ~~(would decrease by ~50.3% globally)~~ affected by severe drought would decline~~ but the affected rural population (would increase by ~73.1% globally) would increase~~ in most regions except for East Africa and South Asia.

~~–~~In general, this comprehensive global drought risk assessment should provide useful insights for international decision-makers to develop informed climate policy within the framework of the 2015 Paris Agreement. Whist most regions would benefit from reduced societal impacts in the 1.5 °C wamer world, l~~This means that l~~ocal governments in East Africa and South Asia should be prepared to deal ~~with — meteorological~~with ~~–~~drought-driven challenges (see paragraph above)~~ in the rural areas (especially in South Asia, Southeast Asia, East Africa and West Africa) relative to the urban areas~~. Future studies on~~are needed to obtain a better~~ understanding ~~of~~the causes of changes in global and regional droughts (~~i.e.,~~e.g., changing pattern/duration of ~~decline in~~precipitation ~~/increase in~~and evaporative demand) with respect to~~under different~~ these warming targets ~~scenarios (1.5 °C and 2 °C), which~~ should assist drought risk adaptation and mitigation planning.~~are very important to the mitigations and adoptions of climate-induced drought risks in the future at both global and regional scales.~~

Data availability. The datasets applied in this study are available at the following locations:

— CMIP5 model experiments (Taylor et al., 2012), https://esgf-data.dkrz.de/projects/esgf-dkrz/

— Spatial population scenarios (Shared Socioeconomic Pathway 1, SSP1, Jones and O'Niell, 2016), https://www2.cgd.ucar.edu/sections/tss/iam/spatial-population-scenarios

Competing interests. The authors declare that they have no conflict of interest.

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Table 1: Details of CMIP5 climate models applied in this study

Climate models	abbreviation	Horizontal Resolution	Future Scenarios
ACCESS1.0	ACCESS	1.300×1.900 degree	RCP4.5, RCP8.5
BCC_CSM1.1	BCC	2.813×2.791 degree	RCP4.5, RCP8.5
BNU-ESM	BNU	2.810×2.810 degree	RCP4.5, RCP8.5
CanESM23	CANESM	2.813×2.791 degree	RCP4.5, RCP8.5
CNRM-CM5	CNRM	1.406×1.401 degree	RCP4.5, RCP8.5
CSIRO Mk3.6.0	CSIRO	1.875×1.866 degree	RCP4.5, RCP8.5
GFDL CM3	GFDL	2.500×2.000 degree	RCP4.5, RCP8.5
INM-CM4.0	INM	2.000×1.500 degree	RCP4.5, RCP8.5
IPSL-CM5B-LR	IPSL	1.875×3.750 degree	RCP4.5, RCP8.5
MRI-CGCM3	MRI	1.125×1.125 degree	RCP4.5, RCP8.5
MIROC-ESM	MIROC	2.813×2.791 degree	RCP4.5, RCP8.5

Table 2: Definition of regions in this study, after IPCC (2012)

ID	abbreviation	Regional Representation
1	ALA	Alaska/Northwest Canada
2	CGI	East Canada, Greenland, Iceland
3	WNA	West North America
4	CNA	Central North America
5	ENA	East North America
6	CAM	Central America and Mexico
7	AMZ	Amazon
8	NEB	Northeastern Brazil
9	WSA	West Coast South America
10	SSA	Southeastern South America
11	NEU	Northern Europe
12	CEU	Central Europe
13	MED	Southern Europe and Mediterranean
14	SAH	Sahara
15	WAF	West Africa
16	EAF	East Africa
17	SAF	Southern Africa
18	NAS	North Asia
19	WAS	West Asia
20	CAS	Central Asia
21	TIB	Tibetan Plateau
22	EAS	East Asia
23	SAS	South Asia
24	SEA	Southeast Asia
25	NAU	North Australia
26	SAU	South Australia/New Zealand
27	GLOBE	Globe

Table 3: Changes in population exposure (including total, urban and rural population, mean ± standard deviation of multi-model projections, unit: million) to severe drought at the globe and in 27 world regions in the 1.5°C and 2°C warmer worlds relative to the baseline period (1985-2006) using the SSP1 population dataset

Regions	1.5°C warming			2.0°C warming		
	Total	Urban	Rural	Total	Urban	Rural
ALA	0.0±0.1	0.0±0.1	0.0±0.0	-0.0±0.1	0.0±0.1	0.0±0.0
CGI	0.1±0.1	0.1±0.1	0.0±0.0	0.0±0.1	0.1±0.1	0.0±0.0
WNA	0.6±1.6	1.8±0.9	-1.2±0.9	1.5±2.6	-1.4±1.1	0.1±0.1
CNA	5.3±8.2	4.5±6.6	0.8±1.7	3.6±5.1	7.8±4.2	0.4±1.0
ENA	4.9±11.6	5.1±10.1	-0.1±1.6	-0.5±6.4	12.3±6.5	-0.6±1.0
CAM	7.1±9.1	10.3±7.9	-3.2±2.2	4.5±6.7	14.8±5.5	-4.6±2.4
AMZ	3.3±2.7	3.9±2.4	-0.6±0.7	4.1±5.6	7.1±4.5	-0.3±1.2
NEB	2.8±3.4	4.7±2.4	-1.9±1.4	4.4±5.4	7.6±4.0	-1.7±1.6
WSA	4.2±4.3	4.1±3.8	0.1±1.6	4.2±4.4	5.8±3.8	0.0±0.5
SSA	5.3±5.2	7.3±4.4	-2.0±1.5	0.6±5.2	8.6±4.8	-2.3±1.5
NEU	3.6±3.9	5.0±3.1	-1.5±1.5	2.6±9.6	8.1±8.1	-2.0±1.8
CEU	12.2±10.5	16.4±8.5	-4.2±3.5	0.7±29.3	27.2±24.2	-5.8±5.2
MED	14.1±6.8	13.3±4.7	0.9±3.4	20.8±21.9	30.6±16.9	0.3±4.9
SAH	2.9±3.7	2.8±1.9	0.1±2.5	6.3±6.7	6.4±4.0	0.3±3.2
WAF	26.6±32.0	26.7±15.7	-0.1±18.0	62.6±78.1	61.9±53.0	-4.5±23.0
EAF	9.3±23.8	11.4±4.0	-2.1±20.9	43.1±33.0	28.0±13.0	-9.4±23.0
SAF	9.2±3.6	7.3±2.1	1.9±1.9	18.9±10.2	18.9±7.8	0.9±2.6
NAS	1.4±6.2	3.0±4.0	-1.6±2.4	-7.9±7.2	3.0±5.2	-2.4±2.4
WAS	11.5±12.5	14.9±7.8	-3.4±5.8	27.1±17.6	28.8±12.8	-3.9±6.0
CAS	7.9±12.3	5.7±6.1	2.2±6.4	4.5±6.7	14.8±5.5	1.2±3.5
TIB	0.9±4.1	0.6±1.6	0.3±2.7	-3.7±3.5	2.4±2.5	-1.0±2.1
EAS	41.5±33.9	44.3±20.6	-2.8±19.8	-17.5±58.1	57.2±41.3	-21.5±24.7
SAS	63.6±86.3	17.7±37.6	45.9±52.4	0.5±72.7	68.5±52.3	-23.1±26.9
SEA	19.4±22.6	19.9±17.0	-0.5±8.2	41.3±21.1	26.1±21.9	-17.2±8.4
NAU	0.1±0.1	0.1±0.1	0.0±0.0	0.2±0.3	0.2±0.3	0.0±0.1
SAU	1.0±1.1	1.1±1.0	-0.1±0.2	3.2±2.0	3.2±1.8	-0.1±0.2
GLOBE	259.3±238.1	232.6±124.8	26.7±119.0	245.8±331.1	468.3±228.0	-99.3±100.2

~~**Table 4:** Changes in population exposure (including total, urban and rural population, mean ± standard deviation of multi-model projections, unit: million) to severe drought at the globe and in 27 world regions in the 1.5°C and 2°C warmer worlds relative to the baseline period using the fixed SSP1 population in 2100 (at the end of the 21st century). The italic numbers in the brackets show the people affected solely by severe droughts under two future warming scenarios, which were calculated using the fixed SSP1 baseline population in 2000 (do not consider the population growth with the development of socioeconomics in the future).~~

Regions	1.5°C warming			2.0°C warming		
	Total	Urban	Rural	Total	Urban	Rural
ALA	0.0±0.1(-0.0±0.1)	0.0±0.1(-0.0±0.1)	0.0±0.0(0.0±0.0)	0.0±0.1(0.0±0.1)	0.0±0.1(0.0±0.1)	0.0±0.0(0.0±
CGI	0.1±0.1(0.0±0.1)	0.0±0.1(0.0±0.0)	0.0±0.0(0.0±0.0)	0.1±0.1(0.0±0.1)	0.0±0.1(0.0±0.0)	0.0±0.0(0.0±
WNA	0.2±1.1(0.2±1.5)	0.2±1.1(0.2±0.6)	0.0±0.0(0.0±0.9)	0.8±1.8(1.1±2.3)	0.8±1.7(0.6±0.8)	0.0±0.1(0.5±
CNA	4.9±10.9(3.1±6.8)	4.5±10.2(2.2±5.0)	0.4±0.7(0.9±1.8)	6.1±6.6(3.8±4.1)	5.6±6.2(2.7±3.0)	0.5±0.4(1.1±
ENA	3.0±17.0(1.9±10.0)	3.0±16.8(1.3±8.2)	0.1±0.2(0.6±2.0)	7.5±9.9(3.4±4.8)	7.4±9.8(0.2±1.5)	0.1±0.1(0.1±
CAM	2.3±7.8(2.1±7.2)	2.2±7.6(0.6±4.0)	0.1±0.2(1.5±3.3)	8.5±9.4(7.8±8.6)	8.2±9.12(3.5±4.6)	0.3±0.3(4.3±
AMZ	2.1±2.0(2.0±2.1)	1.9±1.9(0.9±1.1)	0.2±0.2(1.1±1.1)	4.6±4.3(4.8±4.5)	4.1±3.9(1.6±1.8)	0.5±0.6(3.2±
NEB	1.4±2.3(2.0±3.1)	1.3±2.1(0.6±1.0)	0.1±0.2(1.4±2.1)	3.8±3.6(5.3±4.9)	3.4±3.3(1.4±1.5)	0.4±0.3(3.9±
WSA	4.2±15.1(2.3±3.4)	4.2±14.1(1.9±2.8)	0.1±1.1(0.5±0.7)	13.0±17.9(2.4±2.7)	12.5±16.7(1.8±2.2)	0.5±1.3(0.6±
SSA	2.5±4.1(2.6±4.3)	2.5±4.1(1.5±2.7)	0.0±0.1(1.2±1.9)	3.5±3.8(3.9±4.3)	3.4±3.7(1.9±2.1)	0.1±0.1(2.1±
NEU	3.0±4.7(2.4±3.7)	3.0±4.5(1.5±2.2)	0.1±0.2(0.9±1.5)	4.3±9.7(3.5±7.7)	4.2±9.5(2.2±4.8)	0.1±0.3(1.3±
CEU	10.5±8.7(12.0±10.3)	10.1±8.4(6.4±5.7)	0.4±0.3 (5.5±4.7)	18.4±24.0(22.6±28.2)	17.7±23.0(11.5±14.9)	0.8±1.0(11.1
MED	9.8±6.5(9.0±6.0)	9.2±6.1(3.6±2.2)	0.5±0.5(5.4±4.1)	22.5±17.8(21.1±16.5)	21.2±16.7(8.1±6.6)	1.3±1.1(13.0
SAH	-0.3±7.0(0.2±3.6)	0.0±5.5(0.5±1.6)	-0.3±1.6(-0.3±2.5)	1.7±9.1(1.4±4.7)	1.8±7.2(1.3±2.3)	-0.2±2.1(0.1±
WAF	2.7±71.7(1.9±22.5)	2.9±66.3(0.7±3.2)	-0.2±5.5(1.2±19.5)	14.3±109.5(6.3±34.6)	14.0±101.2(1.9±5.1)	0.3±8.4(4.4±
EAF	-23.7±58.0(-9.2±23.5)	-20.7±51.1(-1.4±3.1)	-3.0±7.0(-7.8±20.6)	-26.3±63.8(-10.2±26.3)	-22.6±56.2(-1.8±3.0)	-3.7±7.7(-8.4
SAF	5.8±4.2(3.2±2.1)	5.2±3.8(1.1±0.6)	0.6±0.5(2.1±1.8)	12.0±9.0(7.3±5.0)	11.0±8.2(2.9±1.5)	1.0±0.8(4.4±
NAS	1.1±4.1(1.7±6.3)	1.1±3.7(0.8±3.3)	0.0±0.4(0.9±3.0)	1.1±5.1(1.7±7.8)	1.0±4.6(0.6±4.1)	0.1±0.5(1.1±
WAS	4.2±15.1(4.7±10.4)	4.2±14.1(1.5±3.0)	0.1±1.1(3.2±7.6)	13.0±17.9(11.8±12.0)	12.5±16.7(3.8±3.5)	0.5±1.3(8.0±
CAS	1.7±15.3(1.6±10.6)	1.0±14.0(0.5±4.7)	0.7±1.5(1.1±6.1)	7.0±9.4(5.3±6.6)	5.5±8.8(1.7±3.2)	1.5±1.0(3.6±
TIB	0.1±3.2(0.3±2.6)	0.0±2.8(-0.0±1.2)	0.1±0.6(0.3±2.5)	0.6±2.9(1.0±3.4)	0.4±2.6(0.2±1.2)	0.2±0.7(0.8±
EAS	17.3±17.8(31.6±34.1)	16.6±16.2(16.4±15.6)	0.7±1.8(15.3±19.9)	24.8±32.8(46.2±64.2)	24.0±30.0(22.8±26.0)	0.9±3.0(23.4
SAS	-15.9±68.8(-12.8±62.4)	-14.9±61.3(-7.7±34.9)	-1.0±8.1(-5.2±31.0)	-35.9±52.6(-31.9±47.7)	-32.3±47.1(-18.3±27.6)	-3.6±6.0(-13.

~~SEA~~	~~1.0±16.1(*0.4±16.2*)~~	~~0.8±15.1(*-0.1±9.1*)~~	~~0.2±1.2(*0.5±8.5*)~~	~~1.5±14.4(*1.0±15.5*)~~	~~1.4±13.2(*0.7±7.2*)~~	~~0.1±1.5 (*0.4±*~~
~~NAU~~	~~0.1±0.1(*0.1±0.1*)~~	~~0.1±0.1(*0.0±0.0*)~~	~~0.0±0.0(*0.0±0.1*)~~	~~0.2±0.3(*0.1±0.2*)~~	~~01±0.2(*0.0±0.1*)~~	~~0.0±0.0 (*0.1±*~~
~~SAU~~	~~0.8±1.7(*0.3±0.8*)~~	~~0.8±17(*0.3±0.6*)~~	~~0.0±0.0(*0.1±0.2*)~~	~~2.4±2.1(*1.1±1.0*)~~	~~2.4±2.1(*0.8±0.7*)~~	~~0.0±0.0(*0.3±*~~
~~GLOBE~~	~~38.6±272.7(*63.8±195.9*)~~	~~38.7±247.1(*33.3±86.6*)~~	~~0.0±26.1(*30.5±113.6*)~~	~~100.3±323.9(*122.4±249.9*)~~	~~99.1±295.9(*55.4±101.8*)~~	~~1.5±28.5(*67.*~~

Figure captions:

Figure 1: Definition of the baseline period, 1.5°C and 2°C warmer worlds based on CMIP5 GCM-simulated changes in global mean temperature (GMT, relative to the pre-industrial levels: 1850-1900). The dark blue and dark yellow shadows indicate the 25th and 75th percentiles of multi-model simulated GMT for RCP 4.5 and RCP 8.5 scenarios, respectively. Both the multi-model ensemble mean and percentiles shown in the figure are smoothed using a moving average approach in a 20-year window

Figure 2: Palmer Drought Severity Index (PDSI)-based drought characteristics definition through the run theory

Figure 3: Changes in multi-model ensemble mean PDSI (i) and model consistency (ii) on a spatial resolution of 0.5° × 0.5°, (a) from the baseline period to 1.5°C warmer world, (b) from the baseline period to 2°C warmer world and (c): ~~from 2°C to 1.5°C~~(a)-(b). Robustness of projections increases with higher model consistency and vice-versa. The dark-gray boxes show the world regions adopted by IPCC (2012), which are labeled in (a)(i) using the ID numbers defined in Table 2. Legend in (a)(i) applies to (b)(i) and (c)(i); legend in (a)(ii) applies to (b)(ii) and (c)(ii).

Figure 4: Multi-model projected PDSI at the globe (66°N-66°S) and in 27 world regions for the baseline period, 1.5°C and 2°C warmer worlds. The projected uncertainty of multiple climate models is shown through box plots for each region and for each period

Figure 5: Changes in multi-model ensemble mean drought duration (months) (i) and model consistency (ii) on a spatial resolution of 0.5° × 0.5°, (a) from the baseline period to 1.5°C warmer world, (b) from the baseline period to 2°C warmer world and (c) : (a)-(b)~~from 2°C to 1.5°C~~. The dark-gray boxes show the regions adopted by IPCC (2012), which are labeled in (a)(i) using the ID numbers defined in Table 2. Legend in (a)(i) applies to (b)(i) and (c)(i); legend in (a)(ii) applies to (b)(ii) and (c)(ii).

Figure 6: Multi-model projected drought duration (months) at the globe (66°N-66°S) and in 27 world regions for the baseline period, 1.5°C and 2°C warmer worlds. The projected uncertainty of multiple climate models is shown through box plots for each region and for each period

Figure 7: Changes in multi-model ensemble mean drought intensity (dimensionless) (i) and model consistency (ii) on a spatial resolution of 0.5° × 0.5°, (a) from the baseline period to 1.5°C warmer world, (b) from the baseline period to 2°C warmer world and (c)~~-~~: (a)-(b)~~from 2°C to 1.5°C~~. The dark-gray boxes show the regions adopted by IPCC (2012), which are labeled in (a)(i) using the ID numbers defined in Table 2. Legend in (a)(i) applies to (b)(i) and (c)(i); legend in (a)(ii) applies to (b)(ii) and (c)(ii).

Figure 8: Multi-model projected drought intensity (dimensionless) at the globe (66°N-66°S) and in 27 world regions for the baseline period, 1.5°C and 2°C warmer worlds. The projected uncertainty of multiple climate models is shown through box plots for each region and for each period

Figure 9: Changes in multi-model ensemble mean drought severity (dimensionless) (i) and model consistency (ii) on a spatial resolution of 0.5° × 0.5°, (a) from the baseline period to 1.5°C warmer world, (b) from the baseline period to 2°C warmer world and (c): (a)-(b) ~~from 2°C to 1.5°C~~. The dark-gray boxes show the regions adopted by IPCC (2012), which are labeled in (a)(i) using the ID numbers defined in Table 2. Legend in (a)(i) applies to (b)(i) and (c)(i); legend in (a)(ii) applies to

(b)(ii) and (c)(ii).

Figure 10: Multi-model projected drought severity (dimensionless) at the globe (66°N-66°S) and in 27 world regions for the baseline period, 1.5°C and 2°C warmer worlds. The projected uncertainty of multiple climate models is shown through box plots for each region and for each period

Figure 11: Multi-model projected frequency (Freq.) and affected total population (Pop., million) of severe drought (~~pdsi~~PDSI < -3) at the globe and in 27 world regions for the baseline period (black, fixed SSP1 2000 population), 1.5°C (orange, fixed SSP1 2100 population) and 2°C (red, fixed SSP1 2100 population) warmer worlds. The projected uncertainties (standard deviation of multiple-model results) of multiple climate models are shown by error bars (horizontal and vertical)

Figure 12: Multi-model projected frequency (Freq.) and affected urban population (Pop., million) of severe drought (~~pdsi~~PDSI < -3) at the globe and in 27 ~~-~~regions for the baseline period (black, fixed SSP1 2000 population), 1.5 °C (orange, fixed SSP1 2100 population) and 2 °C (red, fixed SSP1 2100 population) warmer worlds. The projected uncertainties (standard deviation of multiple-model results) of multiple climate models are shown by error bars (horizontal and vertical)

Figure 13: Multi-model projected frequency (Freq.) and affected rural population (Pop., million) of severe drought (~~pdsi~~PDSI < -3) at the globe and in 27 ~~-~~regions for the baseline period (black, fixed SSP1 2000 population), 1.5 °C (orange, fixed SSP1 2100 population) and 2 °C (red, fixed SSP1 2100 population) warmer worlds. The projected uncertainties (standard deviation of multiple-model results) of multiple climate models are shown by error bars (horizontal and vertical)

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Figure 1: Definition of the baseline period, 1.5°C and 2°C warmer worlds based on CMIP5 GCM-simulated changes in global mean temperature (GMT, relative to the pre-industrial levels: 1850-1900). The dark blue and dark yellow shadows indicate the 25^{th} and 75^{th} percentiles of multi-model simulated GMT for RCP 4.5 and RCP 8.5 scenarios, respectively. Both the multi-model ensemble mean and percentiles shown in the figure are smoothed using a moving average approach in a 20-year window

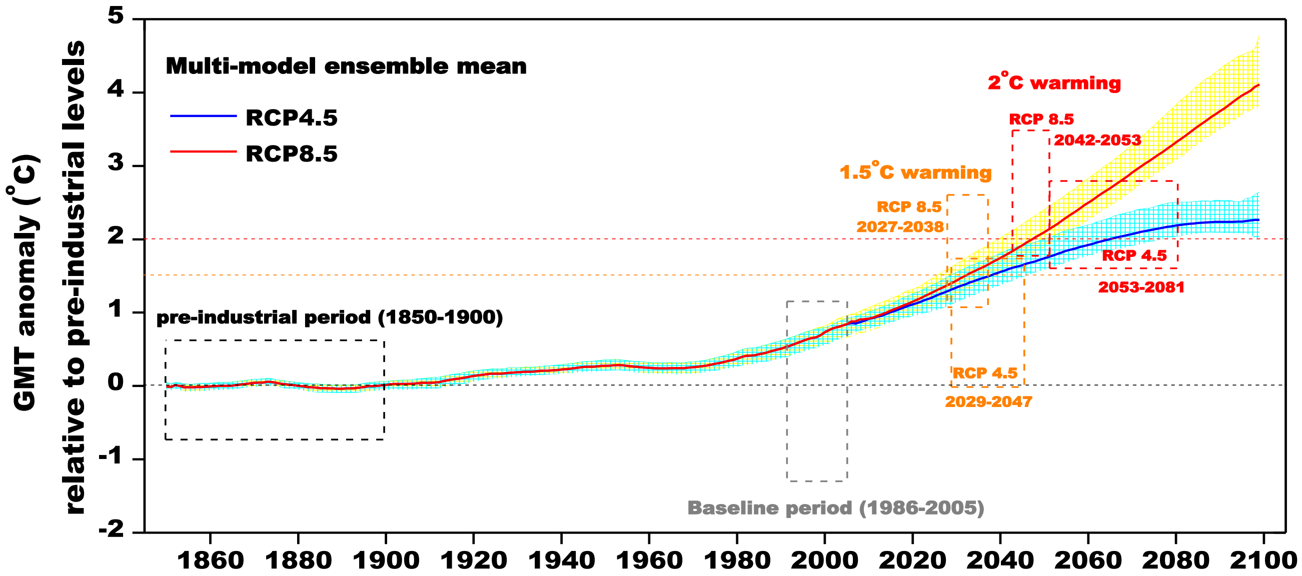

Figure 2: Palmer Drought Severity Index (PDSI)-based drought characteristics definition through the run theory

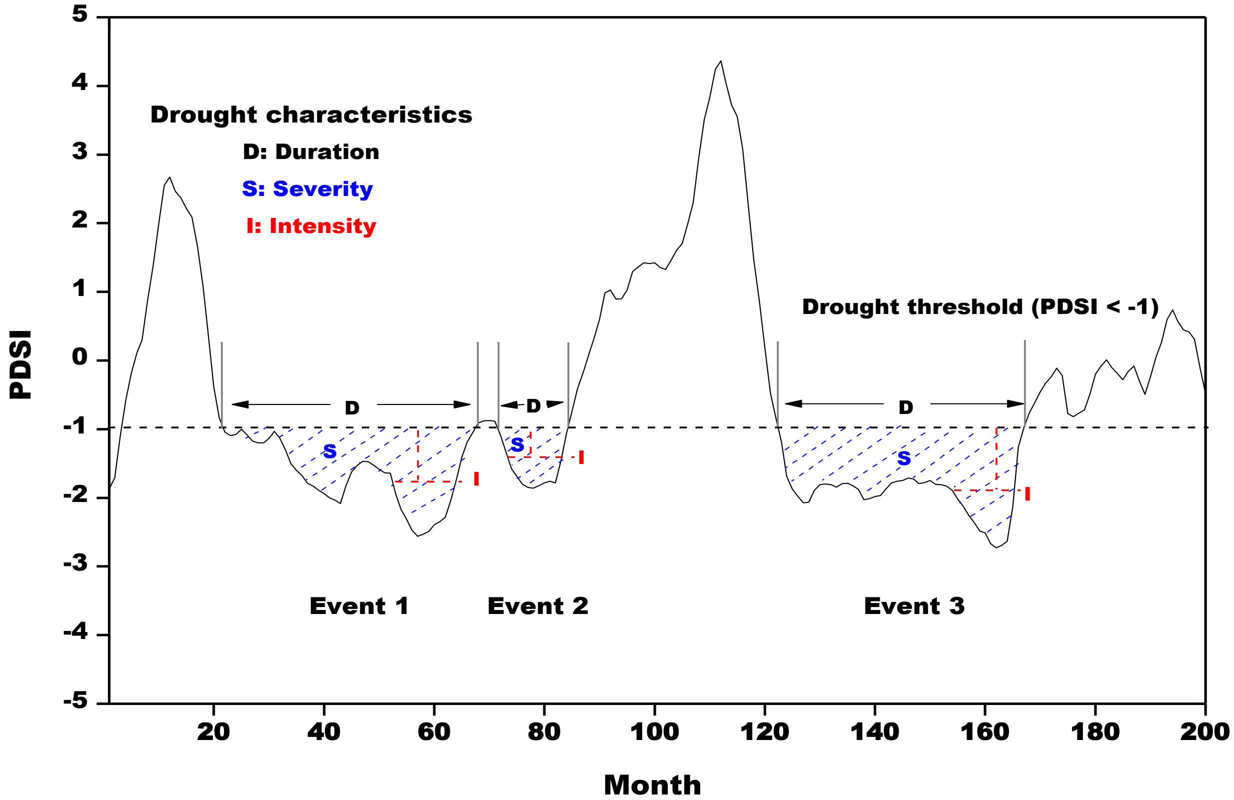

Figure 3: Changes in multi-model ensemble mean PDSI (i) and model consistency (ii) on a spatial resolution of 0.5° × 0.5°, (a) from the baseline period to 1.5°C warmer world, (b) from the baseline period to 2°C warmer world and (c) ~~from 2°C to 1.5°C~~: (a)-(b). Robustness of projections increases with higher model consistency and vice-versa. The dark-gray boxes show the world regions adopted by IPCC (2012), which are labeled in (a)(i) using the ID numbers defined in Table 2. Legend in (a)(i) applies to (b)(i) and (c)(i); legend in (a)(ii) applies to (b)(ii) and (c)(ii).

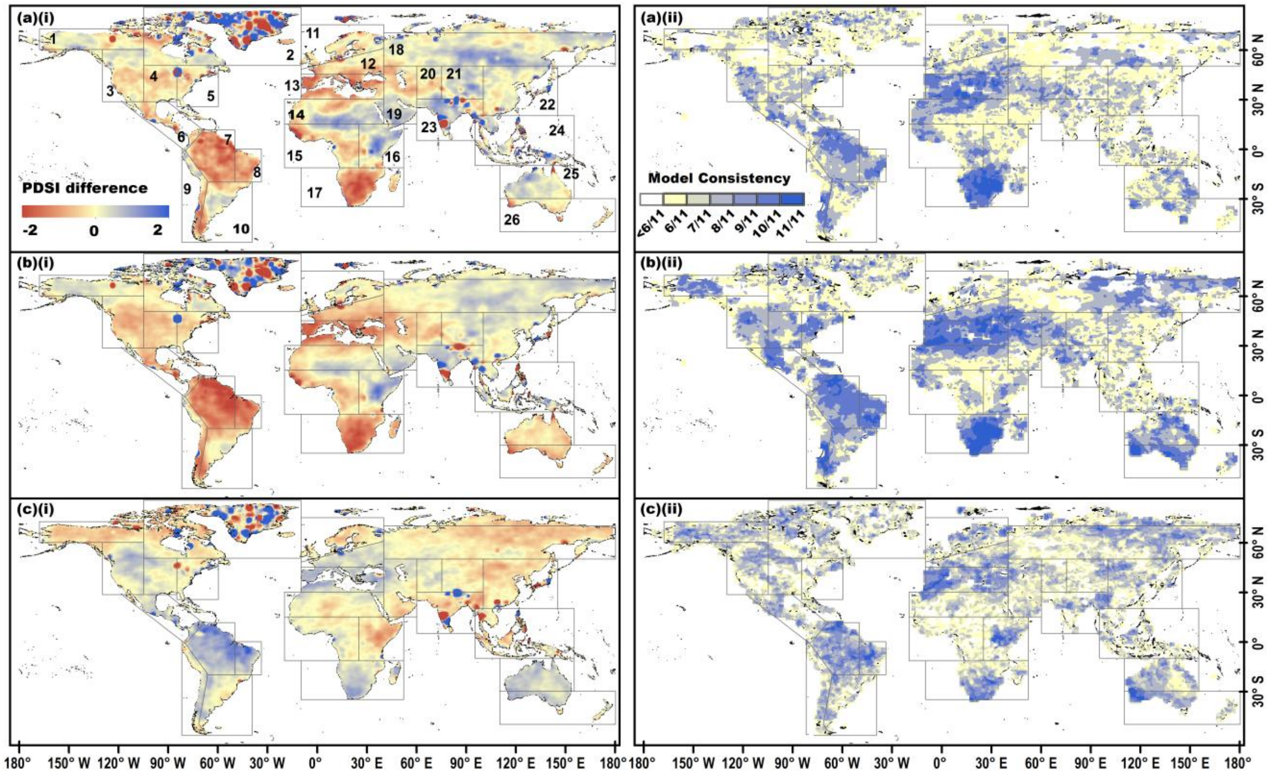

Figure 4: Multi-model projected PDSI at the globe (66^{o}N-66^{o}S) and in 27 world regions for the baseline period, 1.5^{o}C and 2^{o}C warmer worlds. The projected uncertainty of multiple climate models is shown through box plots for each region and for each period

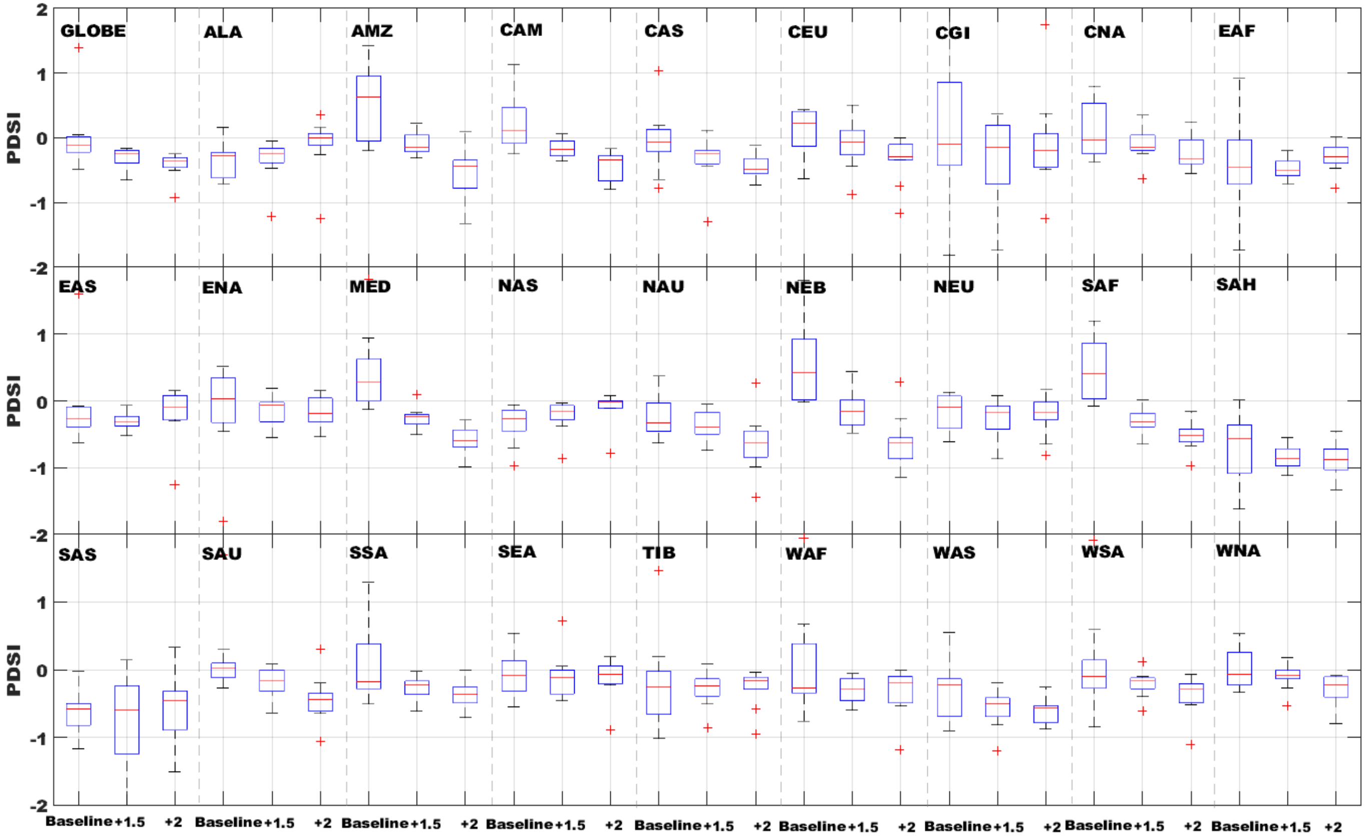

Figure 5: Changes in multi-model ensemble mean drought duration (months) (i) and model consistency (ii) on a spatial resolution of 0.5° × 0.5°, (a) from the baseline period to 1.5°C warmer world, (b) from the baseline period to 2°C warmer world and (c): (a)-(b) ~~from 2°C to 1.5°C~~. The dark-gray boxes show the regions adopted by IPCC (2012), which are labeled in (a)(i) using the ID numbers defined in Table 2. Legend in (a)(i) applies to (b)(i) and (c)(i); legend in (a)(ii) applies to (b)(ii) and (c)(ii).

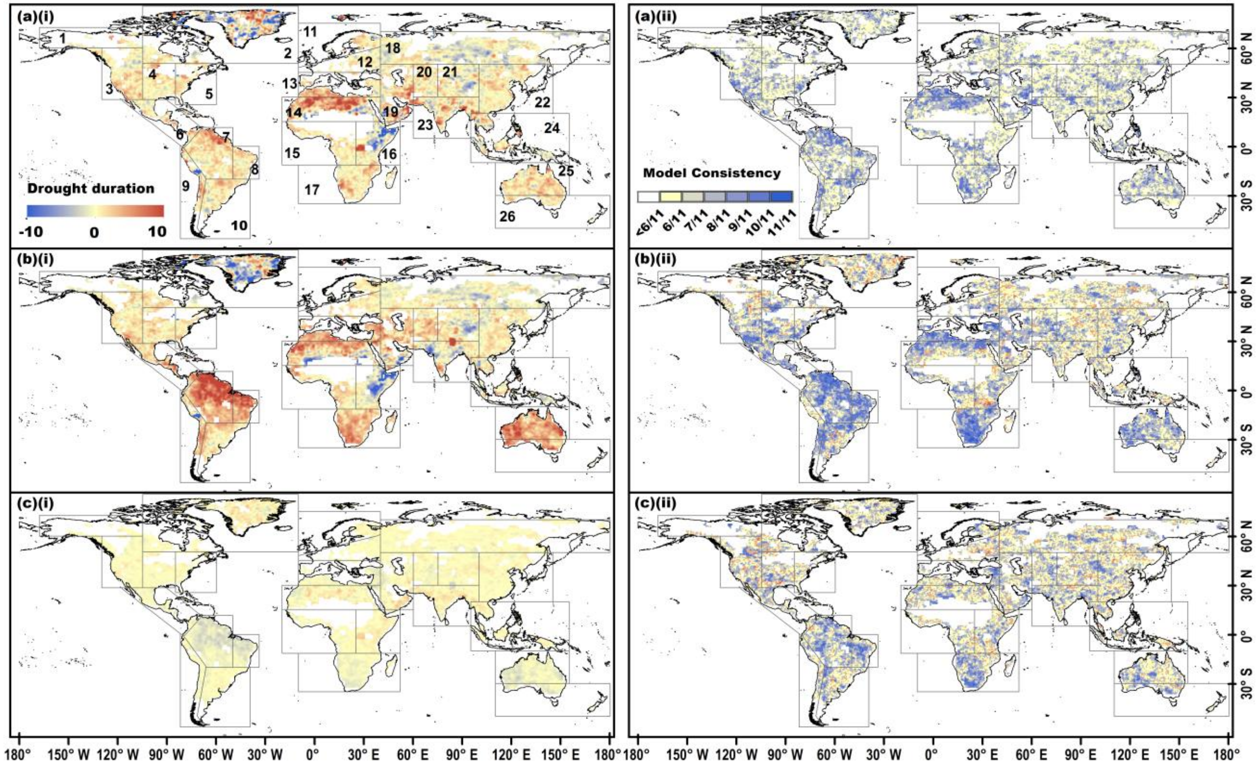

Figure 6: Multi-model projected drought duration (months) at the globe (66°N-66°S) and in 27 regions for the baseline period, 1.5°C and 2°C warmer worlds. The projected uncertainty of multiple climate models is shown through box plots for each region and for each period

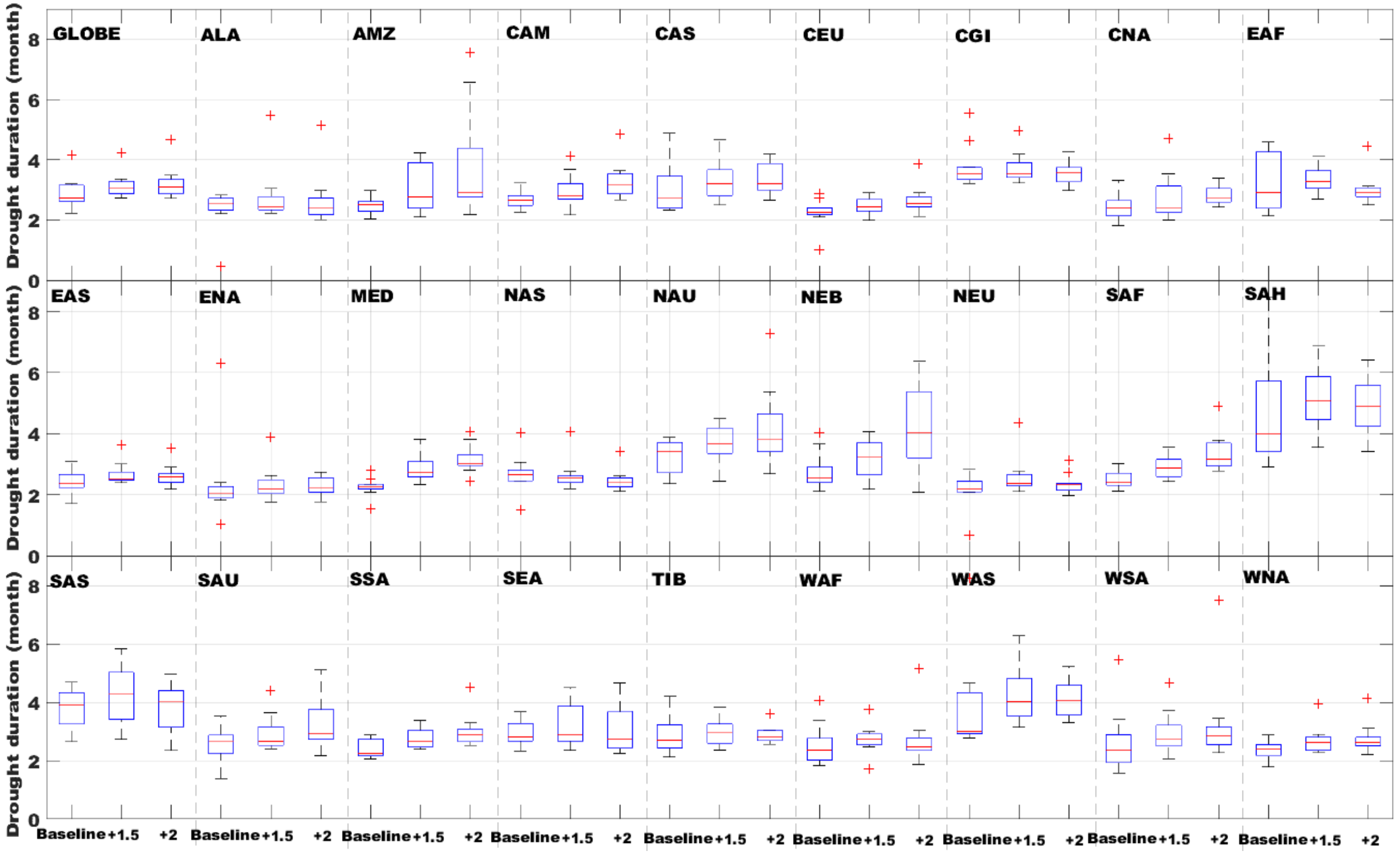

Figure 7: Changes in multi-model ensemble mean drought intensity (dimensionless) (i) and model consistency (ii) on a spatial resolution of 0.5° × 0.5°, (a) from the baseline period to 1.5°C warmer world, (b) from the baseline period to 2°C warmer world and (c): (a)-(b) ~~from 2°C to 1.5°C~~. The dark-gray boxes show the regions adopted by IPCC (2012), which are labeled in (a)(i) using the ID numbers defined in Table 2. Legend in (a)(i) applies to (b)(i) and (c)(i); legend in (a)(ii) applies to (b)(ii) and (c)(ii).

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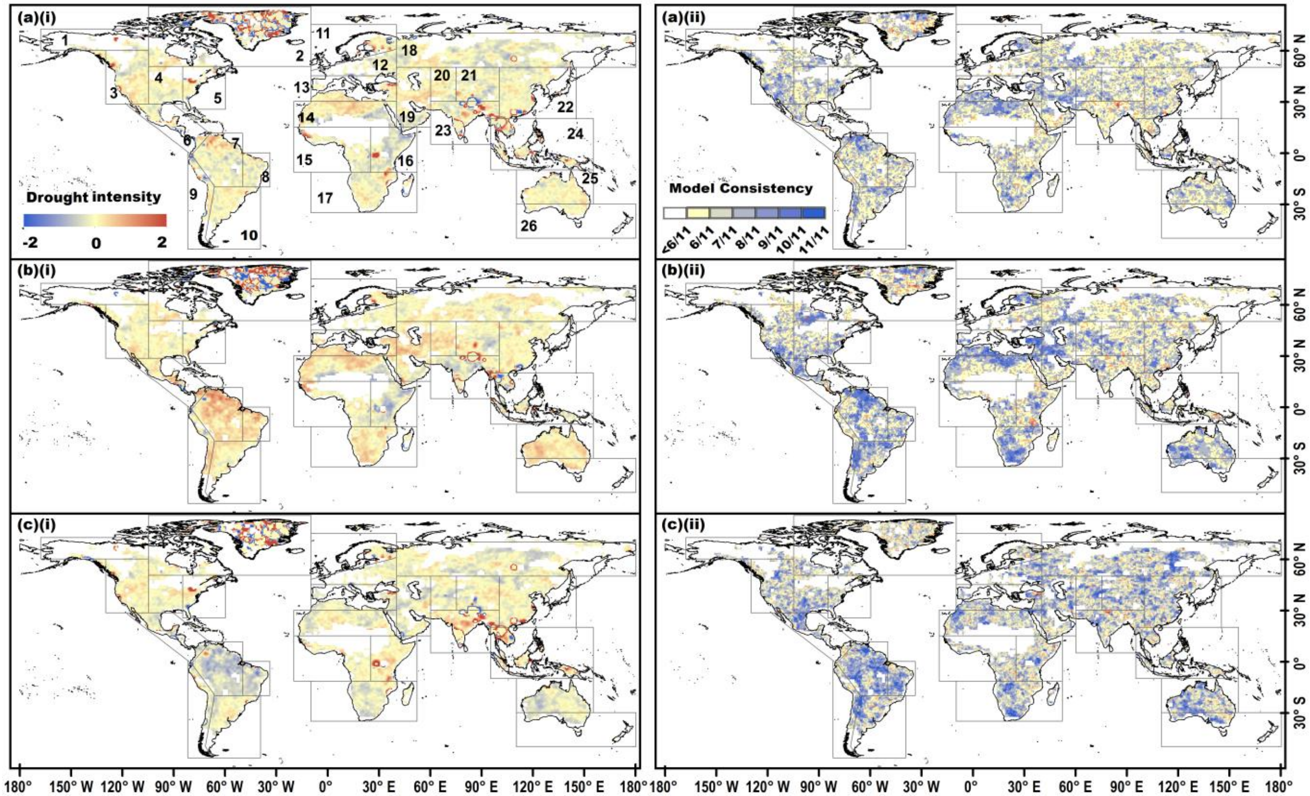

Figure 8: Multi-model projected drought intensity (dimensionless) at the globe (66^{o}N-66^{o}S) and in 27 regions for the baseline period, 1.5^{o}C and 2^{o}C warmer worlds. The projected uncertainty of multiple climate models is shown through box plots for each region and for each period

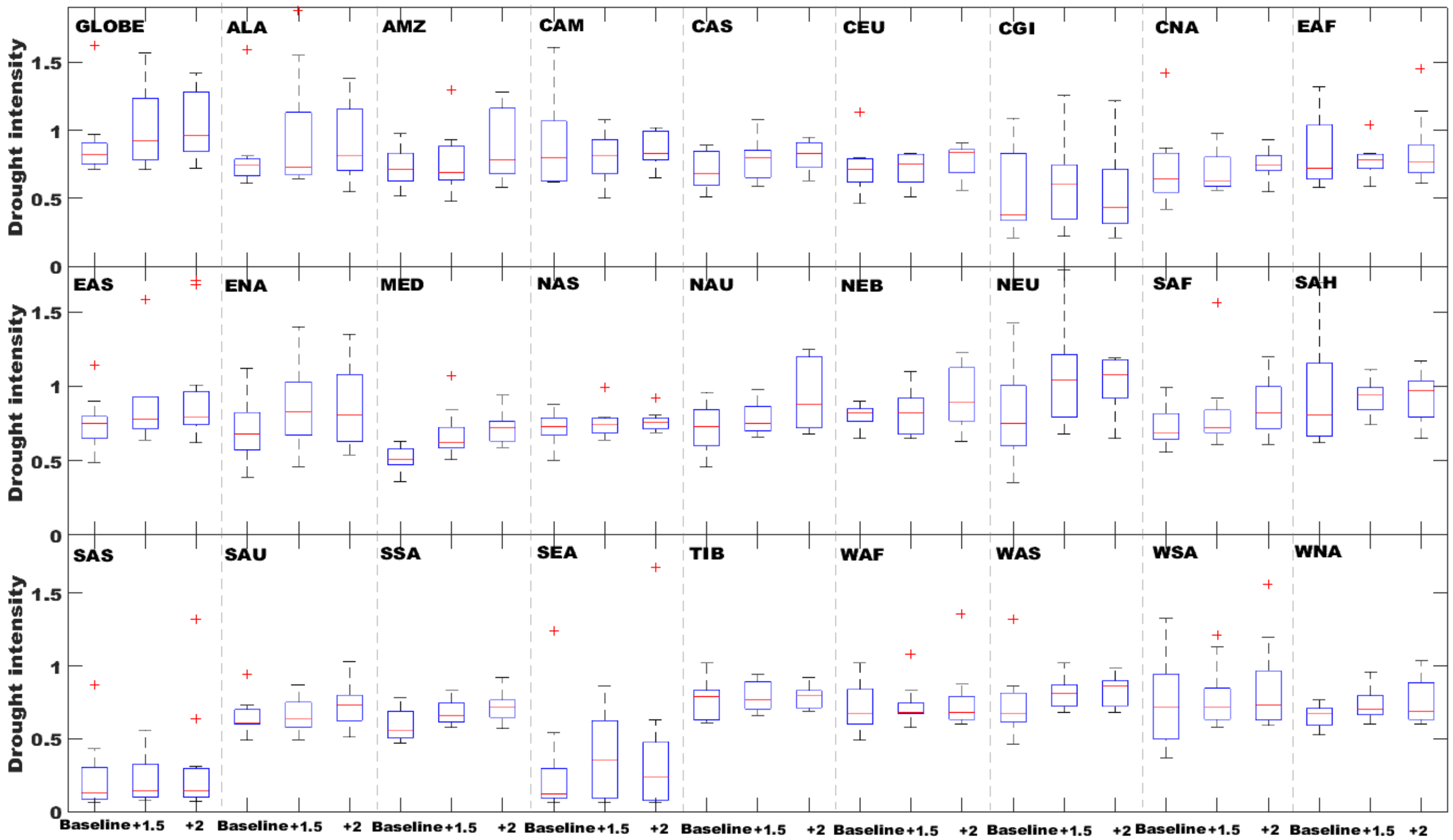

Figure 9: Changes in multi-model ensemble mean drought severity (dimensionless) (i) and model consistency (ii) on a spatial resolution of 0.5° × 0.5°, (a) from the baseline period to 1.5°C warmer world, (b) from the baseline period to 2°C warmer world and (c)~~-~~: (a)-(b)~~from 2°C to 1.5°C~~. The dark-gray boxes show the regions adopted by IPCC (2012), which are labeled in (a)(i) using the ID numbers defined in Table 2. Legend in (a)(i) applies to (b)(i) and (c)(i); legend in (a)(ii) applies to (b)(ii) and (c)(ii).

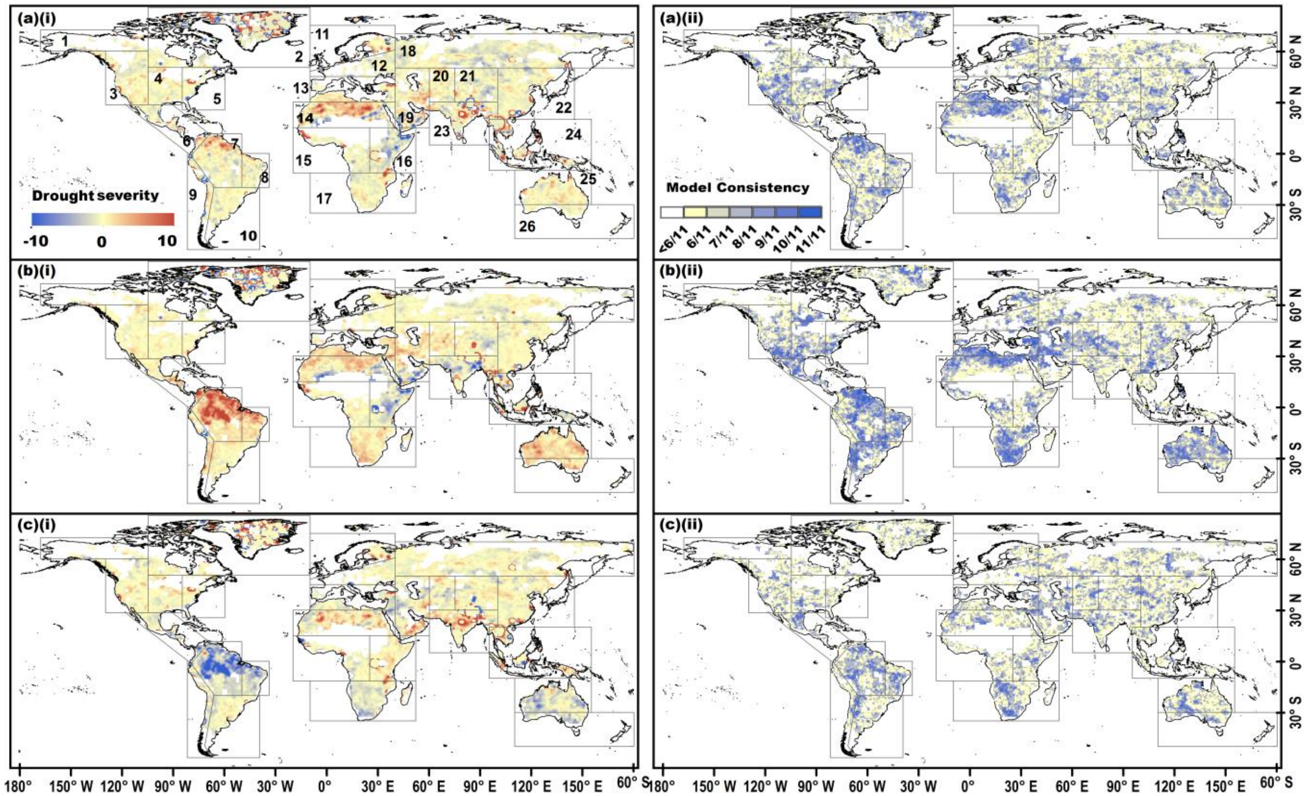

Figure 10: Multi-model projected drought severity (dimensionless) at the globe (66°N-66°S) and in 27 regions for the baseline period, 1.5°C and 2°C warmer worlds. The projected uncertainty of multiple climate models is shown through box plots for each region and for each period

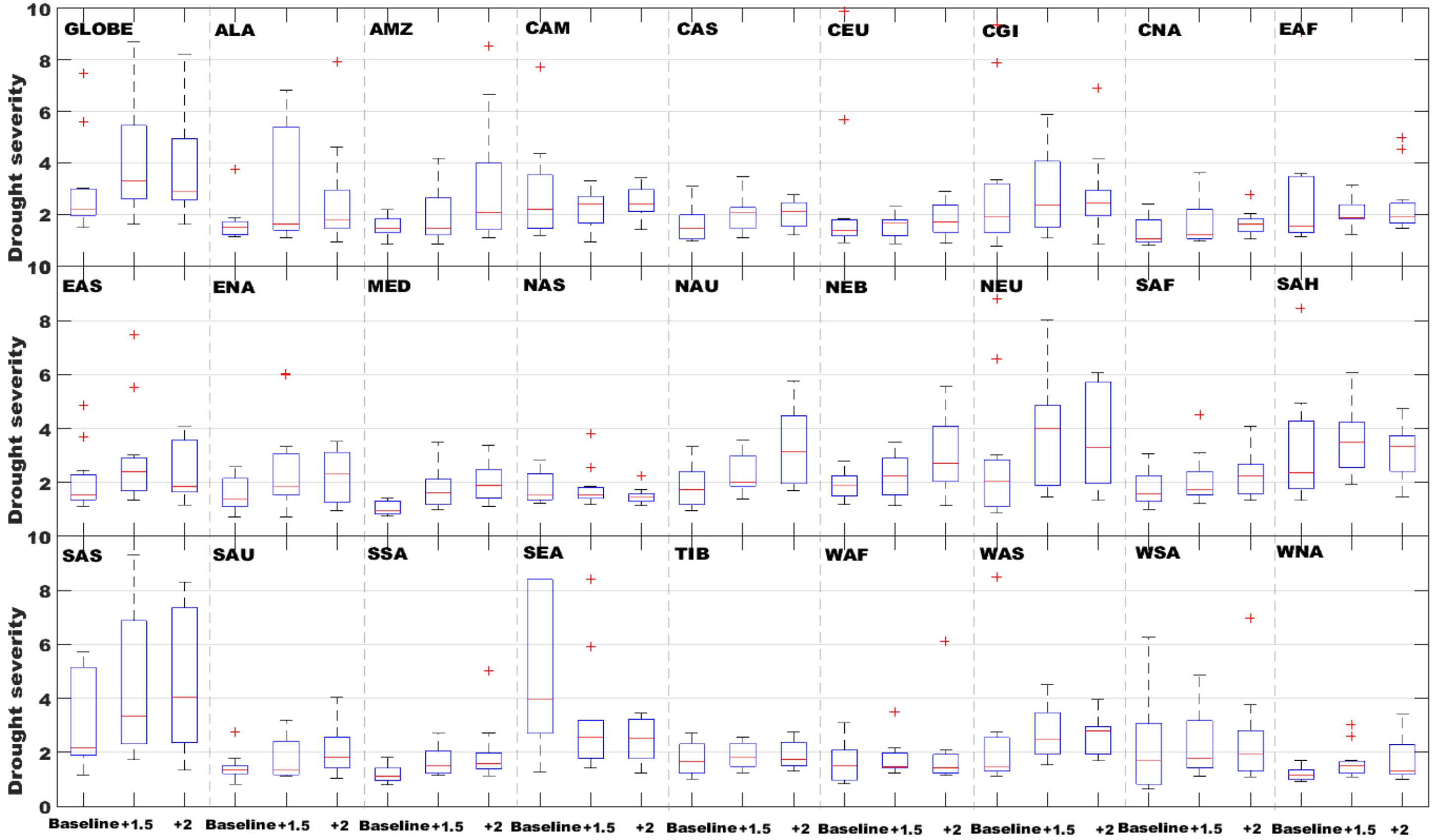

Figure 11: Multi-model projected frequency (Freq.) and affected total population (Pop., million) of severe drought (~~pdsi~~PDSI < -3) at the globe and in 27 regions for the baseline period (black, fixed SSP1 2000 population), 1.5^{o}C (orange, fixed SSP1 2100 population) and 2^{o}C (red, fixed SSP1 2100 population) warmer worlds. The projected uncertainties (standard deviation of multiple-model results) of multiple climate models are shown by error bars (horizontal and vertical)

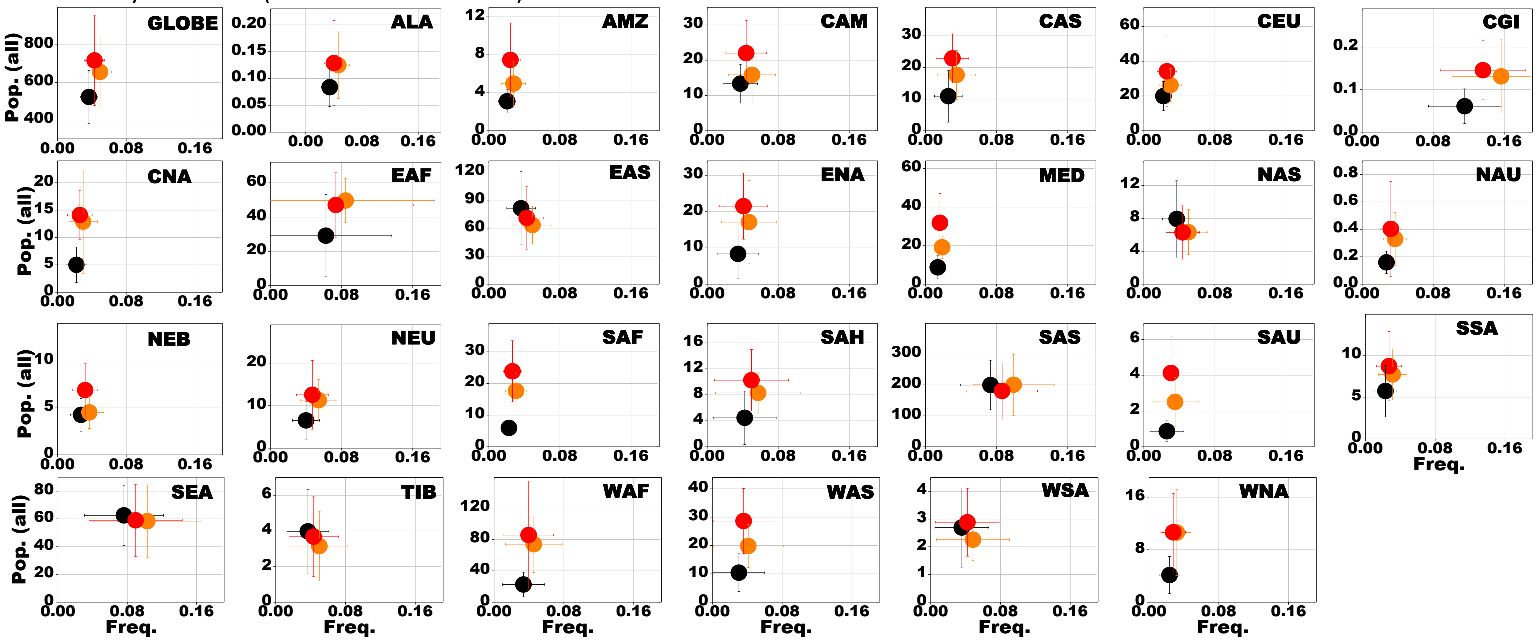

Figure 12: Multi-model projected frequency (Freq.) and affected urban population (Pop., million) of severe drought (~~pdsi~~PDSI < -3) at the globe and in 27 regions for the baseline period (black, fixed SSP1 2000 population), 1.5°C (orange, fixed SSP1 2100 population) and 2°C (red, fixed SSP1 2100 population) warmer worlds. The projected uncertainties (standard deviation of multiple-model results) of multiple climate models are shown by error bars (horizontal and vertical)

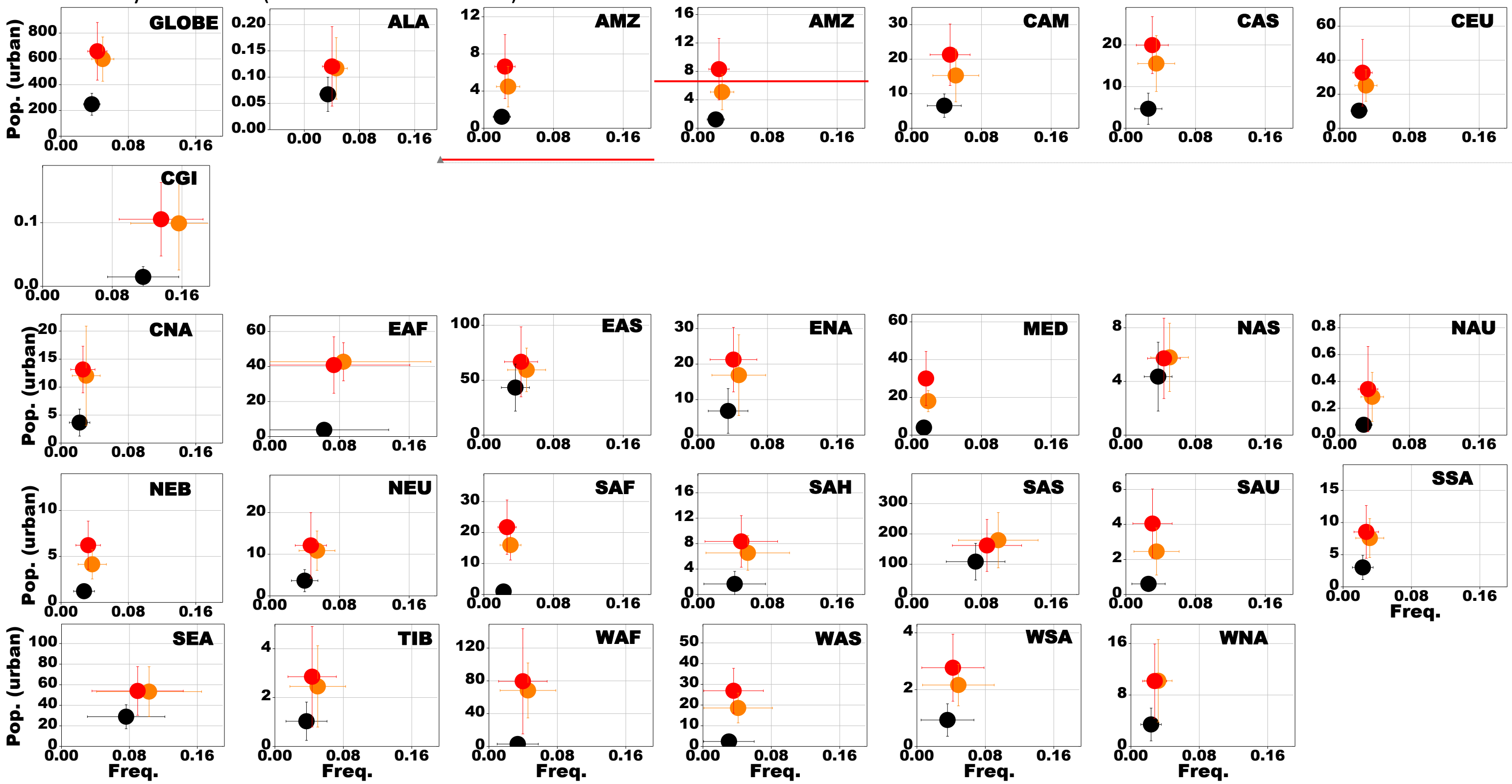

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Figure 13: Multi-model projected frequency (Freq.) and affected rural population (Pop., million) of severe drought (~~pdsi~~PDSI < -3) at the globe and in 27 regions for the baseline period (black, fixed SSP1 2000 population), 1.5°C (orange, fixed SSP1 2100 population) and 2°C (red, fixed SSP1 2100 population) warmer worlds. The projected uncertainties (standard deviation of multiple-model results) of multiple climate models are shown by error bars (horizontal and vertical)