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Less Frequent but More Severe Hydrological Drought Events Emerge at 1.5 and 2 °C Warming Levels over the Wudinghe Watershed in northern China

Yang Jiao[1], Xing Yuan[1*]

[1]Key Laboratory of Regional Climate-Environment for Temperate East Asia (RCE-TEA), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, 100029, China

*Corresponding author address: Xing Yuan, RCE-TEA, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China. E-mail: yuanxing@tea.ac.cn

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Abstract

Assessment of changes in hydrological droughts at specific warming levels (e.g., 1.5 or 2 °C) is important for an adaptive water resources management with consideration of the 2015 Paris Agreement. However, most studies focused on the response of drought frequency to the warming and neglected other drought characteristics including severity. By using a semiarid watershed in northern China (i.e., Wudinghe) as an example, here we show less frequent but more severe hydrological drought events emerge at both 1.5 and 2 °C warming levels. We used meteorological forcings from eight Coupled Model Intercomparison Project Phase 5 climate models with four representative concentration pathways, to drive a newly developed land surface hydrological model to simulate streamflow, and analyzed historical and future hydrological drought characteristics based on the Standardized Streamflow Index. The Wudinghe watershed will reach the 1.5 °C (2 °C) warming level around 2006-2025 (2019-2038), with an increase of precipitation by 6% (9%) and runoff by 17% (27%) as compared to the baseline period (1986-2005). This results in a drop of drought frequency by 26% (27%). However, the drought severity will rise dramatically by 63% (30%), which is mainly caused by the increased variability of precipitation and evapotranspiration. The climate models contribute to more than 82% of total uncertainties in the future projection of hydrological droughts. This study suggests that different aspects of hydrological droughts should be carefully investigated when assessing the impact of 1.5 and 2 °C warming.

Key Words: hydrological drought; global warming; land surface model; CMIP5 models; RCP scenarios; uncertainty analysis.

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1. Introduction

Global warming has affected both natural and artificial systems across continents, bringing a lot of eco-hydrological crises to many countries (Gitay et al., 2002; Tirado et al., 2010; Thornton et al., 2014). The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) concluded that global average surface air temperature increased by 0.61°C in 1986-2005 compared to pre-industrial periods (IPCC, 2014a). In order to mitigate global warming, the Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) emphasized in the Paris Agreement that the increase in global average temperature should be controlled within 2 °C above preindustrial levels, and further efforts should be made to limit it below 1.5 °C. However, a 2 °C warming would be too high for many regions and countries (James et al., 2017; Rogelj et al., 2015). In addition, whether the temperature controlling goal can be reached is still unknown, with much difficulty under current emission conditions (Peters et al., 2012). Therefore, it is necessary to assess changes in hydrological cycle and extremes under 1.5 and 2 °C temperature increases at regional scale.

Global warming is mainly caused by greenhouse gases emissions and has a profound influence on hydrosphere and ecosphere (Barnett et al., 2005; Vorosmarty et al., 2000). It alters hydrological cycle both directly (e.g., influences precipitation and evapotranspiration) and indirectly (e.g., influences plant growth and related hydrological processes) at global (Zhu et al., 2016; McVicar et al., 2012) and local scales (Tang et al., 2013; Zheng et al., 2009; Zhang et al., 2008). Besides affecting the mean states of the hydrological conditions, global warming also intensifies hydrological extremes significantly, such as droughts that were regarded as naturally occurring events when water (precipitation, or streamflow, etc.) is significant below normal over a period of time (Van Loon et al., 2016; Dai, 2011). Among different types of droughts, hydrological droughts focus on the decrease in the availability of water resources, e.g., surface and/or ground water (Lorenzo-Lacruz et al., 2013). Many studies focused on the historical changes, future evolutions, causing factors and uncertainties for hydrological droughts (Chang et al., 2016; Kormos et al., 2016; Orlowsky and Seneviratne, 2013; Parajka et al., 2016; Perez et al., 2011; Prudhomme et al., 2014; Van Loon and Laaha, 2015; Wanders and Wada, 2015; Yuan et al., 2017). Most drought projection studies focused on the future changes over a fixed time period (e.g., the middle and end of the 21st century), but recent studies pointed out the importance on hydrological drought evolution at certain warming levels (Roudier et al., 2016; Marx et al., 2018) given the aim of the Paris Agreement. Moreover, the changes in characteristics (e.g., frequency, duration, severity) of hydrological drought events at specific warming levels received less attention. The projection of these drought characteristics could provide more relevant guidelines for policymakers on implementing adaptation strategies.

In the past five decades, a significant decrease in channel discharge was observed in the middle reaches of the Yellow River basin over northern China (Yuan et al., 2018; Zhao et al., 2014), leading to an intensified water resources scarcity in this populated area. In this study, we take a semiarid watershed, the Wudinghe in the middle reaches

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of the Yellow River basin as a testbed, aiming at solving the following questions: (1) When does temperature increase reach the 1.5 and 2 °C thresholds over the Wudinghe watershed? (2) How do hydrological drought characteristics change at different warming levels? (3) What are the contributions of uncertainties from different sources (e.g., climate models, representative concentration pathways (RCPs) scenarios, and internal variability)?

2. Study area and dataset

In this study, the Wudinghe watershed was selected for hydrological drought analysis. As one of the largest sub-basins of the Yellow River basin, the Wudinghe watershed is located in the Loess Plateau, and has a drainage area of 30261 km^2 with Baijiachuan hydrological station as the watershed outlet (**Figure 1**). It has a semiarid climate with long-term annual mean precipitation of 356 mm and runoff of 39 mm, resulting in a runoff coefficient of 0.11 (Jiao et al., 2017). Most of the rainfall events are concentrated in summer (June to September) with a large possibility of heavy rains (Mo et al., 2009). Located in the transition zone between cropland/grassland and desert/shrub, the northwest part of Wudinghe watershed is dominated by sandy soil, while the major soil type for the southeast part is loess soil. During recent decades, Wudinghe watershed has experienced a significant streamflow decrease (Yuan et al., 2018; Zhao et al., 2014) and suffered from serious water resource scarcity because of climate change, vegetation degradation and human water consumption (Xiao, 2014; Xu, 2011).

The Coupled Model Intercomparison Project Phase 5 (CMIP5) general circulation

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model (GCM) simulations for historical experiments and future projections formed the science basis for the IPCC AR5 reports (IPCC, 2014b; Taylor et al., 2012). In this study, we chose eight CMIP5 GCMs for historical (1961-2005) and future (2006-2099) drought changing analysis. **Table 1** listed the details of GCMs used in this paper. Because of the deficiency in GCM precipitation and runoff simulations, we used the corrected meteorological forcing data from CMIP5 climate models, to drive a land surface hydrological model to simulate runoff and streamflow (see Section 3.1 for details).

All CMIP5 simulations were bias corrected before being used as land surface model input. After interpolating CMIP5 simulations and China Meteorological Administration (CMA) meteorological station observations to a suitable resolution (0.05 degree in this study), a widely used quantile mapping method (Wood et al., 2002; Yuan et al., 2015) was applied to CMIP5/ALL historical simulations to fit its cumulative density functions to observed ones at monthly time scale. For future projections, a modified correction method (Li et al., 2010) was used to remove the biases in CMIP5/RCPs monthly simulations. Bias-corrected monthly precipitation and temperature were then temporally downscaled to a 6-hours interval for driving land surface hydrological model.

3. Land Surface Hydrological Model and Methods

3.1. Introduction of the CLM-GBHM model

In this study, we chose a newly developed land surface hydrological model, CLM-GBHM, to simulate historical and future streamflow. This model was first

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developed and applied in Wudinghe watershed at 0.01 degree (Jiao et al., 2017) and then the Yellow River basin at 0.05 degree resolution (Sheng et al., 2017). By improving surface runoff generation, subsurface runoff scheme, river network-based representation and 1-D kinematic wave river routing processes, CLM-GBHM showed good performances in simulating streamflow, soil moisture content and water table depth (Sheng et al., 2017). **Figure 2** demonstrated the structure and main eco-hydrological processes of CLM-GBHM. Model resolution, surface datasets, initial conditions and model parameters were kept the same as Jiao et al. (2017), except that monthly LAI in 1982 was used for all simulations because of an unknown vegetation condition in the future.

3.2. Determination of years reaching specific warming levels

IPCC AR5 (IPCC, 2014a) reported that global average surface air temperature change between pre-industrial period (1850-1900) and reference period (1986-2005) is 0.61 (0.55 to 0.67) °C. Therefore, we took 1986-2005 as the baseline period, and used "1.5 °C warming level" referring to a temperature increase of 0.89 (=1.5-0.61) °C compared to the baseline. Similarly, "2 °C warming level" referred to an increase of 1.39 (=2-0.61) °C compared to the baseline. As large differences existed in temperature simulations among CMIP5 models and RCP scenarios, we applied a widely used time sampling method (James et al., 2017; Mohammed et al., 2017; Marx et al., 2018) to each GCM under each RCP scenario (referred to as GCM/RCP combination hereafter). A 20-years moving window, which is the length of the baseline period, was used to determine the first period reaching a specific warming level for each combination, with the period median year referred to as the "crossing year".

3.3. Identification of hydrological drought characteristics

We used a two-step method similar to previous studies (Lorenzo-Lacruz et al., 2013; Ma et al., 2015; Yuan et al., 2017) to extract hydrological drought characteristics in this paper. At the first step, a hydrological drought index named as Standardized Streamflow Index (SSI) was calculated by fitting monthly streamflow using a probabilistic distribution function (Vicente-Serrano et al., 2012; Yuan et al., 2017). Specifically, for each calendar month, historical streamflow values in that month were collected, arranged, and fitted by using a gamma distribution function. Using the same parameters of the fitted gamma distribution, both historical (1961-2005) and future (2006-2099) streamflow values in that calendar month were standardized to get SSI values. The procedure was repeated for twelve calendar months, four RCP scenarios and eight GCMs separately. The second step was identification and characterization of hydrological drought events by a SSI threshold method (Yuan and Wood, 2013; Lorenzo-Lacruz et al., 2013; Van Loon and Laaha, 2015). Here, a threshold of -0.8 was selected, which is equivalent to a dry condition with a probability of 20%. Months with SSI below -0.8 were treated as dry months, and 3 or more continuous dry months were considered as the emergence of a hydrological drought event. To characterize the hydrological drought event, drought duration (months) and severity (sum of the difference between -0.8 and SSI) for a certain drought event were calculated.

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3.4. Uncertainty separation

Given large spreads among future projections (including combinations of eight GCMs and four RCP scenarios, as shown in shaded areas in **Figure 3**), a separation method (Hawkins and Sutton, 2009; Orlowsky and Seneviratne, 2013) was applied to explore uncertainty from three individual sources, i.e., internal variability, climate models and RCPs scenarios. In order to separate internal variability from other two factors with long-term changing trends included, a 4th order polynomial was selected to fit specific time series twice: (1) obtain an average i_m during historical period (1961-2005) as a reference value, and (2) obtain a smooth fit $x_{m,s,t}$ during the whole period (1961-2099). Future projections ($X_{m,s,t}$) were separated into three parts: reference value (i_m), smooth fit ($x_{m,s,t}$) and residual ($e_{m,s,t}$), and the uncertainties from three sources were then calculated as follows:

$$V = \sum_m \mathrm{var}_{s,t}(e_{m,s,t}) / N_m \tag{1}$$

$$M_t = \sum_s \mathrm{var}_m(x_{m,s,t}) / N_s \tag{2}$$

$$S_t = \mathrm{var}_s(\sum_m x_{m,s,t} / N_m) \tag{3}$$

where V, M_t and S_t represent uncertainties from internal variability (which is time-invariant), climate models and RCPs scenarios, N_m and N_s are numbers of climate models and RCPs scenarios, $\mathrm{var}_{s,t}$ denotes the variance across scenarios and time, var_m and var_s are variances across models and scenarios respectively. Finally, uncertainty contributions from each component were calculated as proportions to the sum. In this study, we applied this method to the 20-years moving averaged ensemble time series.

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4. Results

4.1. Changes in hydrometeorology in the past and future

We first calculated the trends during both the historical and future periods for basin-averaged annual mean hydrological variables (Table 2 and **Figure 3**). During 1961-2005, there was a significant increasing trend ($p<0.01$) in observed temperature and a decreasing trend ($p<0.1$) in observed precipitation, resulted in a decreasing naturalized streamflow ($p<0.01$) and an increasing hydrological drought frequency ($p<0.01$). Here, the naturalized streamflow was obtained by adding human water use back to the observed streamflow (Yuan et al., 2017). These historical changes could be captured by hydro-climate model simulations to some extent, although both the warming and drying trends were underestimated (Table 2). During 2006-2099, four variables show consistent changing trends across RCPs scenarios, but with different magnitudes (Table 2). Future temperature and precipitation will increase, resulting in an increasing streamflow and decreasing hydrological drought frequency. Unlike temperature trends that increase from RCP2.6 to RCP8.5 (which indicates different radiative forcings), precipitation trend under RCP6.0 is smaller than that under RCP4.5, suggesting a nonlinear response of regional water cycle to the increase in radiative forcings. As a result, RCP6.0 shows the smallest increasing rate in streamflow and decreasing rate in drought frequency.

More details could be found in **Figure 3** when focusing on dynamic changes in the history and future. **Figure 3**a shows that the differences in temperature among RCPs are negligible until 2030s when RCP8.5 starts to outclass other scenarios, and the others begin to diverge in the far future (2060s-2080s). In contrast, differences in future precipitation are small throughout the 21st century, except that RCP8.5 scenario becomes larger after 2080s (**Figure 3**b). As comprehensive outcomes of climate and eco-hydrological factors, a clear decrease-increase pattern in streamflow and an increase-decrease trend in hydrological drought frequency are found (**Figure 3**c and 3d). However, differences among RCPs are not discernible. Figures 3b-3d also show that the differences in water-related variables among climate models are very large.

4.2. Determination of time periods crossing 1.5 and 2 °C warming levels

Using the time-sampling method mentioned in Section 3.2, first 20-year periods with mean temperature increasing across 1.5 and 2 °C warming levels for each GCM/RCP combination were identified and listed in **Table 3**. To demonstrate the overall situation for a specific warming level, we chose median year among GCMs as model ensemble for each RCP scenario, and median year among all GCMs and RCPs as total ensemble.

As listed in **Table 3**, crossing years for most GCM/RCP combinations reaching 1.5 °C warming level are within 2016-2018 except for GFDL-ESM2M and MRI-CGCM3. Model ensemble years for different RCP scenarios have small differences, and total ensemble year for all GCMs and RCPs is 2016, indicating that 1.5 °C warming level would be reached within 2006-2025 over the Wudinghe watershed generally. As for the 2 °C warming level, there are large differences in crossing year from different GCMs. The crossing years vary from 2016 to 2064 among all combinations, where GFDL-ESM2M and MRI-CGCM3 under RCP2.6 scenario will not reach that warming level (marked as "NR" in **Table 3**, and treated as infinity when calculating median year for the ensemble). Model ensemble years for RCP2.6/4.5/6.0/8.5 are 2029/2030/2033/2025 respectively, indicating that the Wudinghe watershed will first reach 2 °C warming level under RCP8.5 and last under RCP6.0 scenario. Overall, the total ensemble year is 2029 for reaching the 2 °C warming level.

4.3. Hydrological changes at 1.5 °C and 2 °C warming levels

After identifying the time periods reaching specific warming levels, we collected precipitation and runoff data within these periods (different among GCM/RCP combinations), and calculated their relative changes compared to the baseline period (1986-2005). **Figure 4** shows the spatial pattern of relative changes in model ensemble mean precipitation. Precipitation increases at both warming levels under all RCP scenarios, while large differences exist in spatial patterns. At 1.5 °C warming level, the watershed-mean changes in precipitation are 5.9% for all scenarios and 7.1%/4.7%/6.6%/5.2% for RCP2.6/4.5/6.0/8.5, respectively. Precipitation increases by nearly 10% at 2 °C warming level for all RCP scenarios, except RCP6.0 by 5.9%. Under all scenarios except RCP6.0, Wudinghe watershed has a larger increase in precipitation at 2°C than 1.5 °C warming level. More precipitation increases occur in the south, west and southwest parts which are upstream regions.

The watershed-mean runoff increases by 17.0% and 26.6%, which are larger than those of precipitation because of nonlinear hydrological response (Figure 5). At 1.5 °C warming level, RCP6.0 shows greatest runoff increase and RCP4.5 the lowest. Negative changes in runoff emerge in the northeast and southeast regions under

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RCP4.5 and RCP8.5 (Figure 5), where precipitation increases least (Figure 4). Moving to 2 °C warming level, mean change rates for runoff are over 25% for RCP2.6/4.5/8.5 scenarios, with RCP8.5 the largest (37%). Runoff changes are closed linked to watershed river networks, with large increase in the south and middle parts (upper and middle reaches) and less increase or even decrease in the southeast and northeast parts (lower reaches).

Figure 6 shows the characteristics of hydrological droughts during the baseline period and the periods reaching both warming levels. The number of hydrological drought events averaged among all RCP scenarios and climate models is 10.2 in the baseline period, and it drops to 7.5 (-26% relative to baseline, the same below) at 1.5 °C warming level and 7.4 (-27%) at 2 °C warming level (**Figure 6**a). Hydrological drought durations do not change significantly, with 6.4, 6.7 (+5%) and 6.0 (-6%) months at baseline, 1.5 and 2 °C warming levels, respectively. However, drought severity increases from 2.7 at baseline to 4.4 (+63%) at 1.5 °C warming level, and then to 3.5 (+30%) at 2 °C warming level (**Figure 6**a). These results indicate that although precipitation and runoff increase, the Wudinghe watershed would suffer from more severe hydrological events in the near future at 1.5 °C warming level. The severity could be alleviated in time periods reaching 2 °C warming level, with more precipitation occurring over the watershed.

The results for individual scenarios also suggest a decrease in drought frequency, but an increase in drought severity (Figures 6b-6e). The least change in drought severity is found under RCP2.6 scenario (+4%/+15% after warming). Under RCP8.5, drought duration increases from 6.4 to 7.8 (+22%) and 8.6 (+34%) months, and drought severity increases from 2.7 to 5.9 (+119%) and 7.9 (+193%). In short, high emissions would increase the risk of hydrological drought over the Wudinghe watershed significantly through increasing the duration and severity.

5. Discussion

To explore the reason for less frequent but more severe hydrological droughts, we compared the differences in monthly precipitation, evapotranspiration, total/surface/sub-surface runoff and streamflow between baseline and periods reaching 1.5 °C and 2 °C warming levels. Standardized indices for these hydrological variables were used to remove seasonality from monthly time series, and mean values and variabilities of these indices were chosen as indicators.

Figure 7 shows that mean values increase as temperature increases for all standardized hydrological indices, showing a wetter hydroclimate in the near future with more precipitation, evapotranspiration, runoff and streamflow (**Figure 7**a). However, variabilities for the standardized indices in the future are higher than those during baseline period, indicating larger fluctuations and higher chance for extreme droughts/floods at both warming levels (**Figure 7**b). Focusing on the gaps between baseline and future periods (**Figure 7**a-7b), it is clear that the differences in both evapotranspiration and runoff are much larger than those of precipitation for both mean values and standard deviations, suggesting the water redistribution through complicated hydrological processes. The increase in mean value of runoff and consequently streamflow mainly comes from the increase in subsurface runoff. As hydrological drought defined in this paper is based on monthly SSI series, increases in both mean value and variability in precipitation and evapotranspiration indicate a period with less frequent but more severe hydrological drought events.

Another issue is the reliability of results considering large differences among CMIP5 models. Figure 8 shows the uncertainty fractions contributed from internal variability, climate models and RCPs scenarios based on multi-model and multi-scenario ensemble projections of temperature, precipitation, streamflow and drought frequency. Uncertainty in temperature projection is mainly contributed by climate models before 2052, and it is then taken over by RCPs scenarios. Internal variability contributes to less than 3% of the uncertainty for the temperature projection (Figure 8a). For precipitation projection, climate models account for a large proportion of uncertainty (over 73%) throughout the century. The internal variability contributes to larger uncertainty than RCPs scenarios until the second half of the 21st century (Figure 8b). Similar to precipitation, major source of uncertainty for the projections of streamflow and hydrological drought frequency comes from climate models, while the impacts of both internal variability and RCP scenarios are further weakened (Figures 8c-8d).

For total ensemble (see **Table 4**), climate model accounts for over 80% of total uncertainties for all variables, while internal variability contributes to a comparable or larger proportion than RCPs scenarios except for temperature. RCPs scenario uncertainty accounts for 18.4% of temperature uncertainty and 4.8% of precipitation uncertainty at 2 ℃ warming level, both of them are more than doubled compared to those at 1.5 ℃ warming level. RCPs scenario only contributes to around 3% of the uncertainties in the projections of streamflow and hydrological drought frequency. These results indicate that the improvement in GCMs would largely narrow the uncertainties for future projections of hydrological droughts.

There are also some issues for further investigations. As shown in Figure 3, GCM historical simulations underestimates the increasing trend in temperature and decreasing trend in precipitation, and results in underestimations of hydrological drying trends. Although the quantile mapping method used in this study is able to remove the biases in GCM simulations (e.g., mean value, variance), the underestimation of trends could not be corrected. An alternative method is to use regional climate models for dynamical downscaling, which would be useful if regional forcings (e.g., topography, land use change, aerosol emission) are strong. Another issue is about the spatially varied warming rates. IPCC AR5 reported (IPCC, 2014c) that global warming for the last 20 years compared to pre-industrial are 0.3-1.7 °C (RCP2.6), 1.1-2.6 °C (RCP4.5), 1.4-3.1 °C (RCP6.0), 2.6-4.8 °C (RCP8.5). However, temperature increases vary a lot for different regions. For instance, temperature rises faster in high-altitude (Kraaijenbrink et al., 2017) and polar regions (Bromwich et al., 2013), where the rate of regional warming could be three times of global warming. In this paper, we focused on local warming rates in our studying area with a conclusion that both warming levels could probably be reached in the near future. The reaching periods for regional warming levels are earlier than global mean results (not shown here), which suggest that the hydrological droughts would probably be more severe under global warming of 1.5 and 2 °C scenarios.

6. Conclusions

In this paper, we bias-corrected future projections of meteorological forcings from eight CMIP5 GCM simulations under four RCP scenarios to drive a newly developed land surface hydrological model, CLM-GBHM, to project changes in streamflow and hydrological drought characteristics over the Wudinghe watershed. After determining the local time periods reaching 1.5 °C and 2 °C warming levels for each GCM/RCP combination, we focused on the changes in hydrological drought characteristics at both warming levels. Moreover, projection uncertainties from different sources were separated and analyzed. Main conclusions are listed as follows:

(1) With CMIP5 GCM simulations as forcing data, the model ensemble mean hindcast can reproduce the significant decreasing trend of streamflow and increasing trend of hydrological drought frequency in historical period (1961-2005), but the drying trend is underestimated because of GCM uncertainties. Streamflow increases and hydrological drought frequency decreases in the future under all RCP scenarios.

(2) The time periods reaching 1.5 °C and 2 °C warming levels over the Wudinghe watershed are 2006-2025 and 2019-2038, respectively. Different RCP scenarios show small deviations in time periods reaching 1.5 °C warming level, while results vary for reaching the 2 °C warming level, with RCP8.5 the earliest and RCP6.0 the latest.

(3) Precipitation increases under all RCP scenarios at both warming levels (5.9% and 9.0%), while large differences exist in spatial patterns. Runoff has larger relative change rates (17.0% and 26.6%). Large increases of runoff occurred in the upper and middle reaches and less increases or even decreases emerged in the lower reaches,

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indicating a complex spatial distribution in hydrological droughts.

(4) As a result of increasing mean values and variability for precipitation, evapotranspiration and runoff, hydrological drought frequency drops by 26-27% at both warming levels compared to the baseline period, while hydrological drought severity rises dramatically by 63% at 1.5 °C warming level and then drops to 30% at 2 °C warming level. This indicates that the Wudinghe watershed would suffer more severe hydrological drought events in the future, especially under RCP6.0 and RCP8.5 scenarios.

(5) The main uncertainty sources vary among hydrological variables. In the near future, most uncertainties are from climate models, especially for precipitation. At both warming levels, climate models contribute to over 82% of total uncertainties, while internal variability contributes to a comparable proportion of uncertainties to RCPs scenarios for precipitation, streamflow and hydrological drought frequency.

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References

Barnett, T. P., Adam, J. C., and Lettenmaier, D. P.: Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438, 303-309, doi:10.1038/nature04141, 2005.

Bromwich, D. H., Nicolas, J. P., Monaghan, A. J., Lazzara, M. A., Keller, L. M., Weidner, G. A., and Wilson, A. B.: Central West Antarctica among the most rapidly warming regions on Earth, Nat Geosci, 6, 139-145, doi:10.1038/Ngeo1671, 2013.

Chang, J., Li, Y., Wang, Y., and Yuan, M.: Copula-based drought risk assessment combined with an integrated index in the Wei River Basin, China, Journal of Hydrology, 540, 824-834, doi:10.1016/j.jhydrol.2016.06.064, 2016.

Dai, A. G.: Drought under global warming: a review, Wires Clim Change, 2, 45-65, doi:10.1002/wcc.81, 2011.

Gitay, H., Suárez, A., Watson, R. T., and Dokken, D. J.: Climate change and biodiversity, IPCC Technical Paper V, 2002.

Hawkins, E., and Sutton, R.: The Potential to Narrow Uncertainty in Regional Climate Predictions, B Am Meteorol Soc, 90, 1095-+, doi:10.1175/2009bams2607.1, 2009.

IPCC: Climate Change 2013 - The Physical Science Basis, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp., 2014a.

IPCC: Summary for Policymakers, in: Climate Change 2013 - The Physical Science Basis, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1-30, 2014b.

IPCC: Long-term Climate Change: Projections, Commitments and Irreversibility, in: Climate Change 2013 - The Physical Science Basis, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge,

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United Kingdom and New York, NY, USA, 1029-1136, 2014c.

James, R., Washington, R., Schleussner, C. F., Rogelj, J., and Conway, D.: Characterizing half-a-degree difference: a review of methods for identifying regional climate responses to global warming targets, Wires Clim Change, 8, doi:10.1002/wcc.457, 2017.

Jiao, Y., Lei, H. M., Yang, D. W., Huang, M. Y., Liu, D. F., and Yuan, X.: Impact of vegetation dynamics on hydrological processes in a semi-arid basin by using a land surface-hydrology coupled model, Journal of Hydrology, 551, 116-131, doi:10.1016/j.jhydrol.2017.05.060, 2017.

Kormos, P. R., Luce, C. H., Wenger, S. J., and Berghuijs, W. R.: Trends and sensitivities of low streamflow extremes to discharge timing and magnitude in Pacific Northwest mountain streams, Water Resour Res, 52, 4990-5007, doi:10.1002/2015wr018125, 2016.

Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F., and Immerzeel, W. W.: Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers, Nature, 549, 257-+, doi:10.1038/nature23878, 2017.

Li, H. B., Sheffield, J., and Wood, E. F.: Bias correction of monthly precipitation and temperature fields from Intergovernmental Panel on Climate Change AR4 models using equidistant quantile matching, J Geophys Res-Atmos, 115, doi:10.1029/2009jd012882, 2010.

Lorenzo-Lacruz, J., Moran-Tejeda, E., Vicente-Serrano, S. M., and Lopez-Moreno, J. I.: Streamflow droughts in the Iberian Peninsula between 1945 and 2005: spatial and temporal patterns, Hydrology and Earth System Sciences, 17, 119-134, doi:10.5194/hess-17-119-2013, 2013.

Ma, F., Yuan, X., and Ye, A. Z.: Seasonal drought predictability and forecast skill over China, J Geophys Res-Atmos, 120, 8264-8275, doi:10.1002/2015jd023185, 2015.

Marx, A., Kumar, R., Thober, S., Rakovec, O., Wanders, N., Zink, M., Wood, E. F., Pan, M., Sheffield, J., and Samaniego, L.: Climate change alters low flows in Europe under global warming of 1.5, 2, and 3 degrees C, Hydrology and Earth

System Sciences, 22, 1017-1032, doi:10.5194/hess-22-1017-2018, 2018.

McVicar, T. R., Roderick, M. L., Donohue, R. J., Li, L. T., Van Niel, T. G., Thomas, A., Grieser, J., Jhajharia, D., Himri, Y., Mahowald, N. M., Mescherskaya, A. V., Kruger, A. C., Rehman, S., and Dinpashoh, Y.: Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation, Journal of Hydrology, 416, 182-205, doi:10.1016/j.jhydrol.2011.10.024, 2012.

Mo, X. G., Liu, S. X., Chen, D., Lin, Z. H., Guo, R. P., and Wang, K.: Grid-size effects on estimation of evapotranspiration and gross primary production over a large Loess Plateau basin, China, Hydrolog Sci J, 54, 160-173, doi:10.1623/hysj.54.1.160, 2009.

Mohammed, K., Islam, A. S., Islam, G. M. T., Alfieri, L., Bala, S. K., and Khan, M. J. U.: Extreme flows and water availability of the Brahmaputra River under 1.5 and 2 A degrees C global warming scenarios, Climatic Change, 145, 159-175, doi:10.1007/s10584-017-2073-2, 2017.

Orlowsky, B., and Seneviratne, S. I.: Elusive drought: uncertainty in observed trends and short- and long-term CMIP5 projections, Hydrology and Earth System Sciences, 17, 1765-1781, doi:10.5194/hess-17-1765-2013, 2013.

Parajka, J., Blaschke, A. P., Bloeschl, G., Haslinger, K., Hepp, G., Laaha, G., Schoener, W., Trautvetter, H., Viglione, A., and Zessner, M.: Uncertainty contributions to low-flow projections in Austria, Hydrology and Earth System Sciences, 20, 2085-2101, doi:10.5194/hess-20-2085-2016, 2016.

Perez, G. A. C., van Huijgevoort, M. H. J., Voss, F., and van Lanen, H. A. J.: On the spatio-temporal analysis of hydrological droughts from global hydrological models, Hydrology and Earth System Sciences, 15, 2963-2978, doi:10.5194/hess-15-2963-2011, 2011.

Peters, G. P., Andrew, R. M., Boden, T., Canadell, J. G., Ciais, P., Le Quéré, C., Marland, G., Raupach, M. R., and Wilson, C.: The challenge to keep global warming below 2 C, Nat Clim Change, 3, 4, 2012.

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arnell, N. W., Dankers, R., Fekete, B. M., Franssen, W., Gerten, D., Gosling, S. N., Hagemann, S., Hannah, D. M., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y., and Wisser, D.: Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment, Proceedings of the National Academy of Sciences, 111, 3262-3267, doi:10.1073/pnas.1222473110, 2014.

Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., and Riahi, K.: Energy system transformations for limiting end-of-century warming to below 1.5 degrees C, Nat Clim Change, 5, 519-+, doi:10.1038/nclimate2572, 2015.

Roudier, P., Andersson, J. C. M., Donnelly, C., Feyen, L., Greuell, W., and Ludwig, F.: Projections of future floods and hydrological droughts in Europe under a+2 degrees C global warming, Climatic Change, 135, 341-355, doi:10.1007/s10584-015-1570-4, 2016.

Sheng, M. Y., Lei, H. M., Jiao, Y., and Yang, D. W.: Evaluation of the Runoff and River Routing Schemes in the Community Land Model of the Yellow River Basin, J Adv Model Earth Sy, 9, 2993-3018, doi:10.1002/2017ms001026, 2017.

Tang, Y., Tang, Q., Tian, F., Zhang, Z., and Liu, G.: Responses of natural runoff to recent climatic variations in the Yellow River basin, China, Hydrology and Earth System Sciences, 17, 4471-4480, doi: 10.5194/hess-17-4471-2013, 2013.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An Overview of Cmip5 and the Experiment Design, B Am Meteorol Soc, 93, 485-498, doi:10.1175/Bams-D-11-00094.1, 2012.

Thornton, P. K., Ericksen, P. J., Herrero, M., and Challinor, A. J.: Climate variability and vulnerability to climate change: a review, Global Change Biol, 20, 3313-3328, doi:10.1111/gcb.12581, 2014.

Tirado, M. C., Clarke, R., Jaykus, L. A., McQuatters-Gollop, A., and Franke, J. M.: Climate change and food safety: A review, Food Res Int, 43, 1745-1765, doi:10.1016/j.foodres.2010.07.003, 2010.

Van Loon, A. F., and Laaha, G.: Hydrological drought severity explained by climate and catchment characteristics, Journal of Hydrology, 526, 3-14,

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-255
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 16 July 2018

Hydrology and Earth System Sciences
Open Access
Discussions

doi:10.1016/j.jhydrol.2014.10.059, 2015.

Van Loon, A. F., Stahl, K., Di Baldassarre, G., Clark, J., Rangecroft, S., Wanders, N., Gleeson, T., Van Dijk, A. I. J. M., Tallaksen, L. M., Hannaford, J., Uijlenhoet, R., Teuling, A. J., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., and Van Lanen, H. A. J.: Drought in a human-modified world: reframing drought definitions, understanding, and analysis approaches, Hydrology and Earth System Sciences, 20, 3631-3650, doi:10.5194/hess-20-3631-2016, 2016.

Vicente-Serrano, S. M., Lopez-Moreno, J. I., Begueria, S., Lorenzo-Lacruz, J., Azorin-Molina, C., and Moran-Tejeda, E.: Accurate Computation of a Streamflow Drought Index, J Hydrol Eng, 17, 318-332, doi:10.1061/(Asce)He.1943-5584.0000433, 2012.

Vorosmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B.: Global water resources: Vulnerability from climate change and population growth, Science, 289, 284-288, doi:10.1126/science.289.5477.284, 2000.

Wanders, N., and Wada, Y.: Human and climate impacts on the 21st century hydrological drought, Journal of Hydrology, 526, 208-220, doi:10.1016/j.jhydrol.2014.10.047, 2015.

Wood, A. W., Maurer, E. P., Kumar, A., and Lettenmaier, D. P.: Long-range experimental hydrologic forecasting for the eastern United States, J Geophys Res-Atmos, 107, doi:10.1029/2001jd000659, 2002.

Xiao, J. F.: Satellite evidence for significant biophysical consequences of the "Grain for Green" Program on the Loess Plateau in China, J Geophys Res-Biogeo, 119, 2261-2275, doi:10.1002/2014jg002820, 2014.

Xu, J. X.: Variation in annual runoff of the Wudinghe River as influenced by climate change and human activity, Quatern Int, 244, 230-237, doi:10.1016/j.quaint.2010.09.014, 2011.

Yuan, X., and Wood, E. F.: Multimodel seasonal forecasting of global drought onset, Geophys Res Lett, 40, 4900-4905, doi:10.1002/grl.50949, 2013.

Yuan, X., Roundy, J. K., Wood, E. F., and Sheffield, J.: Seasonal forecasting of

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-255
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 16 July 2018

Hydrology and Earth System Sciences
Open Access
Discussions

global hydrologic extremes: system development and evaluation over GEWEX basins, B Am Meteorol Soc, 96, 1895-1912, doi:10.1175/BAMS-D-14-00003.1, 2015.

Yuan, X., Zhang, M., Wang, L. Y., and Zhou, T.: Understanding and seasonal forecasting of hydrological drought in the Anthropocene, Hydrology and Earth System Sciences, 21, 5477-5492, doi:10.5194/hess-21-5477-2017, 2017.

Yuan, X., Y. Jiao, D. Yang, and H. Lei: Reconciling the attribution of changes in streamflow extremes from a hydroclimate perspective, Water Resour Res, doi:10.1029/2018WR022714, 2018

Zhang, X. P., Zhang, L., Zhao, J., Rustomji, P., and Hairsine, P.: Responses of streamflow to changes in climate and land use/cover in the Loess Plateau, China, Water Resour Res, 44, doi:10.1029/2007wr006711, 2008.

Zhao, G. J., Tian, P., Mu, X. M., Jiao, J. Y., Wang, F., and Gao, P.: Quantifying the impact of climate variability and human activities on streamflow in the middle reaches of the Yellow River basin, China, Journal of Hydrology, 519, 387-398, doi:10.1016/j.jhydrol.2014.07.014, 2014.

Zheng, H. X., Zhang, L., Zhu, R. R., Liu, C. M., Sato, Y., and Fukushima, Y.: Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin, Water Resour Res, 45, doi:10.1029/2007wr006665, 2009.

Zhu, Z. C., Piao, S. L., Myneni, R. B., Huang, M. T., Zeng, Z. Z., Canadell, J. G., Ciais, P., Sitch, S., Friedlingstein, P., Arneth, A., Cao, C. X., Cheng, L., Kato, E., Koven, C., Li, Y., Lian, X., Liu, Y. W., Liu, R. G., Mao, J. F., Pan, Y. Z., Peng, S. S., Penuelas, J., Poulter, B., Pugh, T. A. M., Stocker, B. D., Viovy, N., Wang, X. H., Wang, Y. P., Xiao, Z. Q., Yang, H., Zaehle, S., and Zeng, N.: Greening of the Earth and its drivers, Nat Clim Change, 6, 791-795, doi:10.1038/nclimate3004, 2016.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-255
Manuscript under review for journal Hydrol. Earth Syst. Sci.
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Figure Captions

Figure 1. Location, elevation and river networks for the Wudinghe watershed.

Figure 2. Structure and main eco-hydrological processes for the land surface hydrological model CLM-GBHM. (modified from Jiao et al., 2017)

Figure 3. Historical (ALL) and future (RCP2.6/4.5/6.0/8.5) time series of standardized annual mean (a) temperature, (b) precipitation and (c) streamflow, and (d) the time series of hydrological drought frequency (drought months for each year) over the Wudinghe watershed. Shaded areas indicate the ranges between maximum and minimum values among CMIP5/CLM-GBHM model simulations. ALL represents historical simulations with both anthropogenic and natural forcings, RCP2.6/4.5/6.0/8.5 represent four representative concentration pathways from lower to higher emission scenarios.

Figure 4. Spatial pattern of relative changes in multi-model ensemble mean precipitation at 1.5 ℃ and 2 ℃ warming levels compared to the baseline period (1986-2005). The percentages in the upper-right corners of each panel are the watershed-mean changes for different RCP scenarios, and the percentages in the top brackets are the mean values from four RCP scenarios.

Figure 5. The same as **Figure 4**, but for the spatial patterns of runoff changes.

Figure 6. Comparison of the characteristics (frequency (number of drought events per 20 years), duration (months) and severity) averaged among climate models and RCP scenarios for hydrological drought events during the baseline period (1986-2005) and the periods reaching 1.5 ℃ and 2 ℃ warming levels.

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Figure 7. Comparison of (a) mean values and (b) standard deviations for hydrological indices averaged among climate models and RCP scenarios during the baseline period (1986-2005) and the periods reaching 1.5 °C and 2 °C warming levels. SPI, SEI, SRI, SSRI, SBI, SSI represent standardized indices of precipitation, evapotranspiration, runoff, surface runoff, baseflow (subsurface runoff) and streamflow, respectively.

Figure 8. Fractions of uncertainties from internal variability (orange), RCP scenarios (green) and climate models (blue) for the projections of 20-years moving averaged (a) temperature, (b) precipitation (c) streamflow and (d) hydrological drought frequency. Two dashed lines indicate the multi-model ensemble median years reaching 1.5 °C (year 2016) and 2 °C (year 2029) warming levels, respectively.

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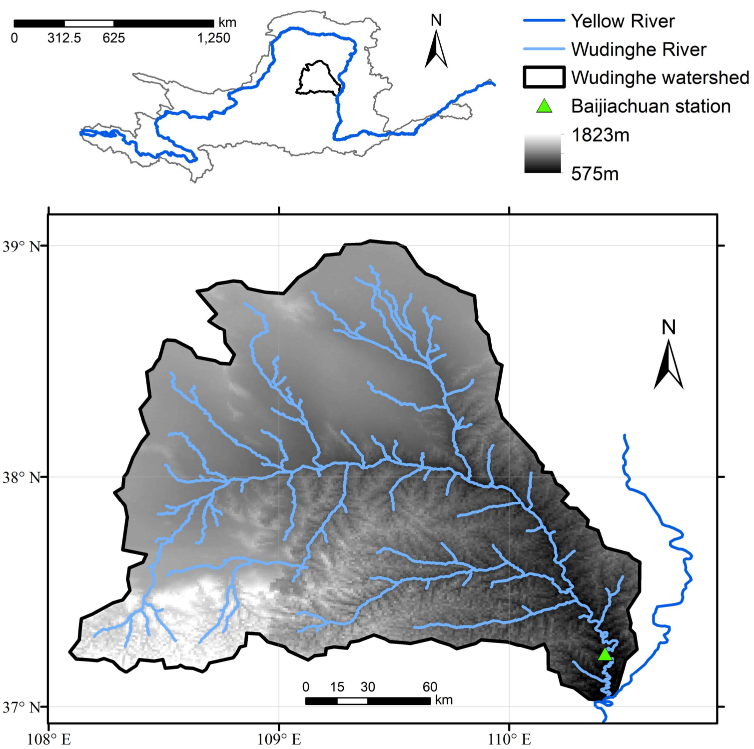
Table 4. Uncertainty contributions (%) from internal variability, climate models and RCPs scenarios for the future projections considering 1.5 ℃ and 2 ℃ warming levels.



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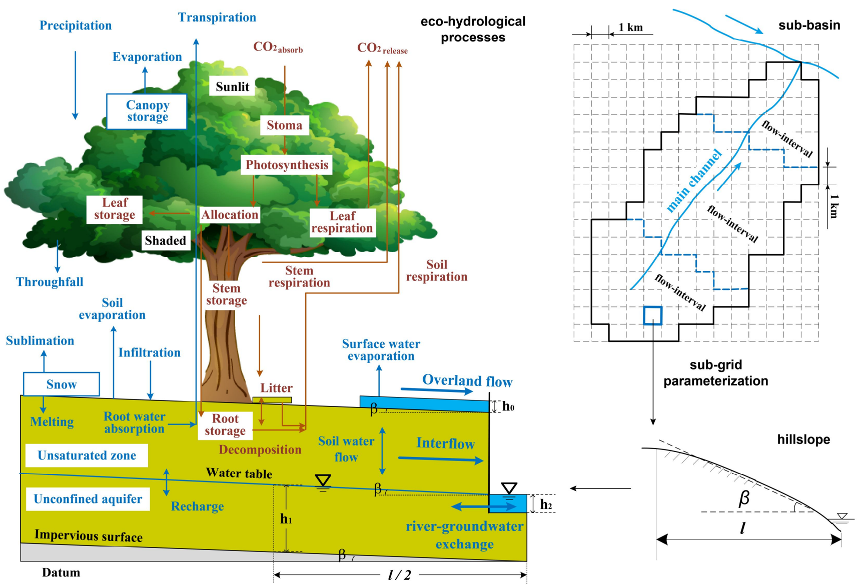

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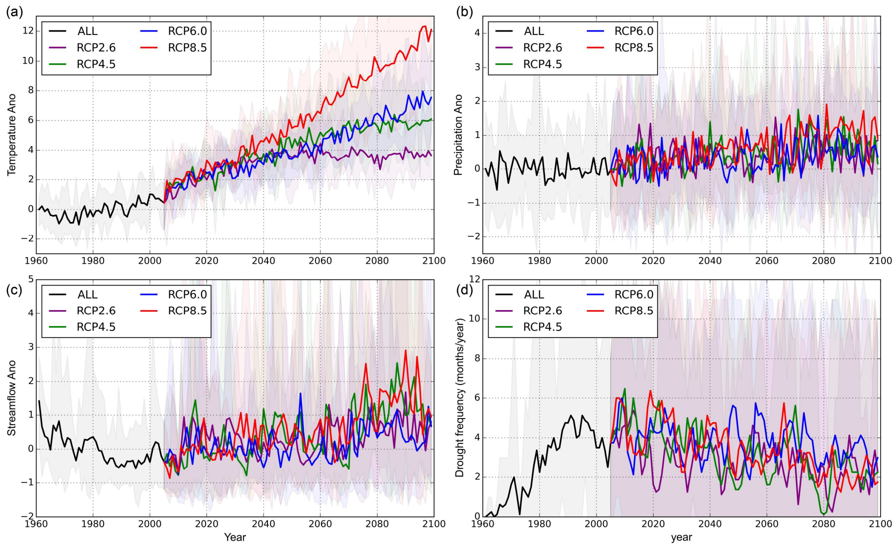

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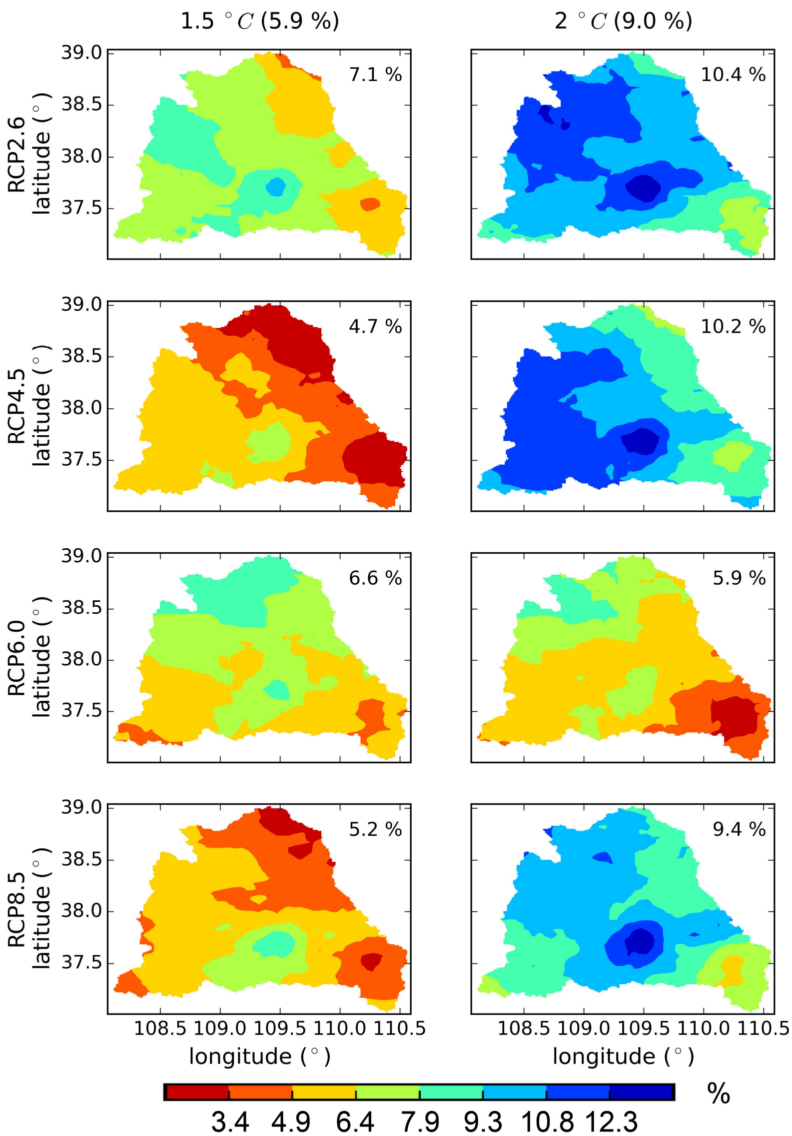

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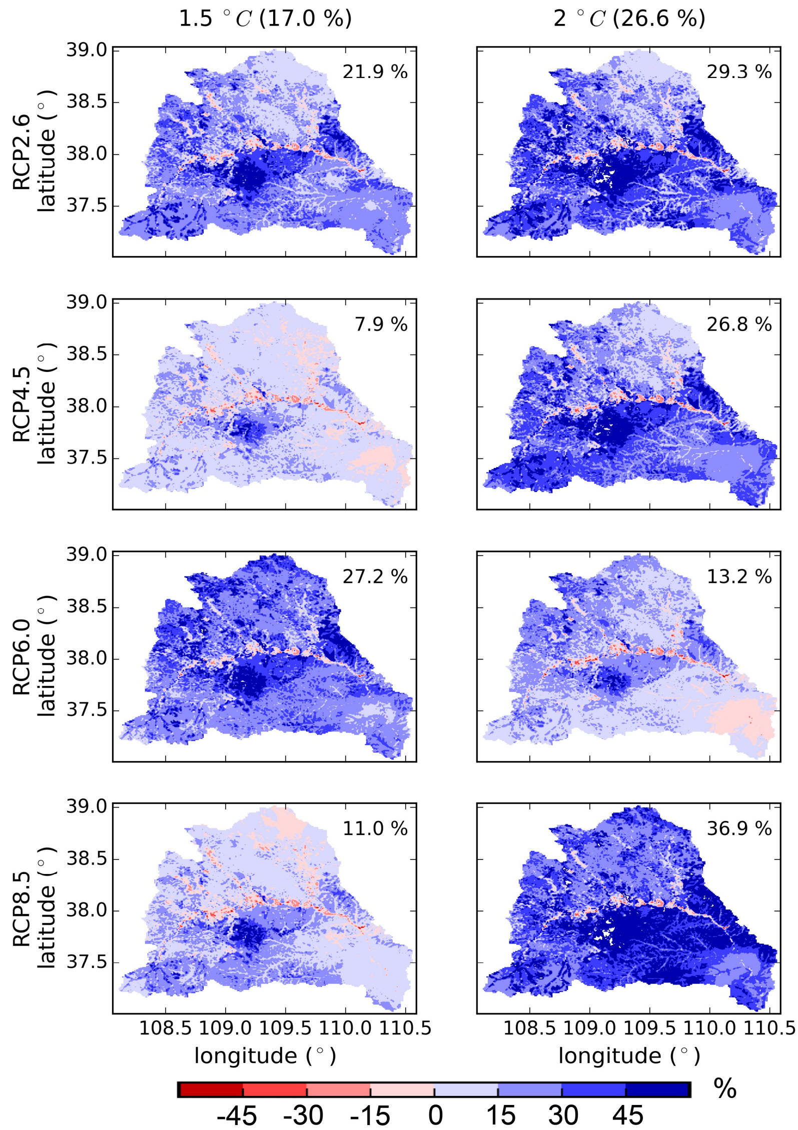

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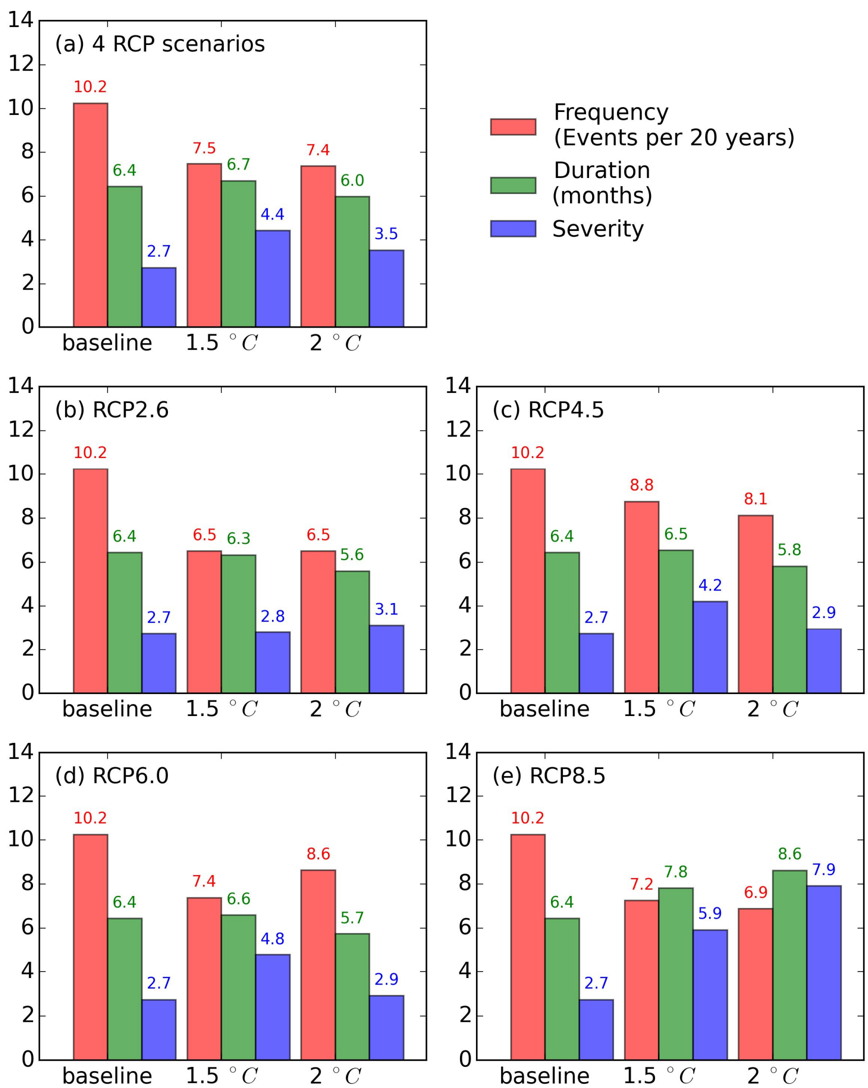

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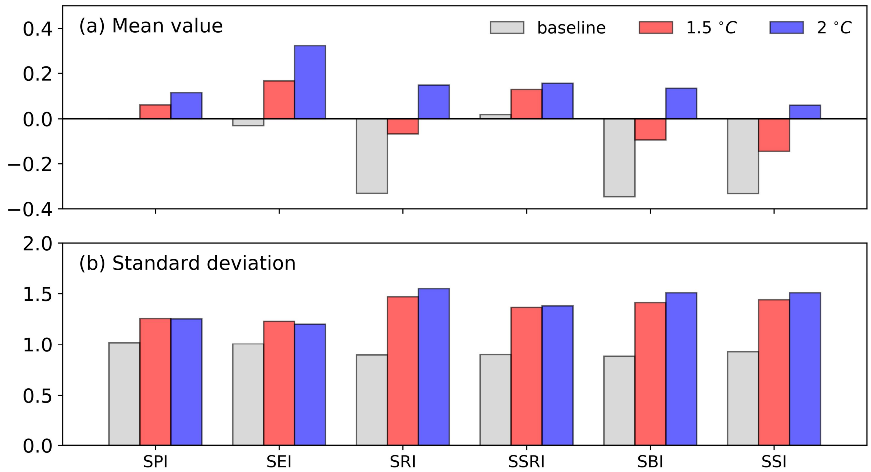

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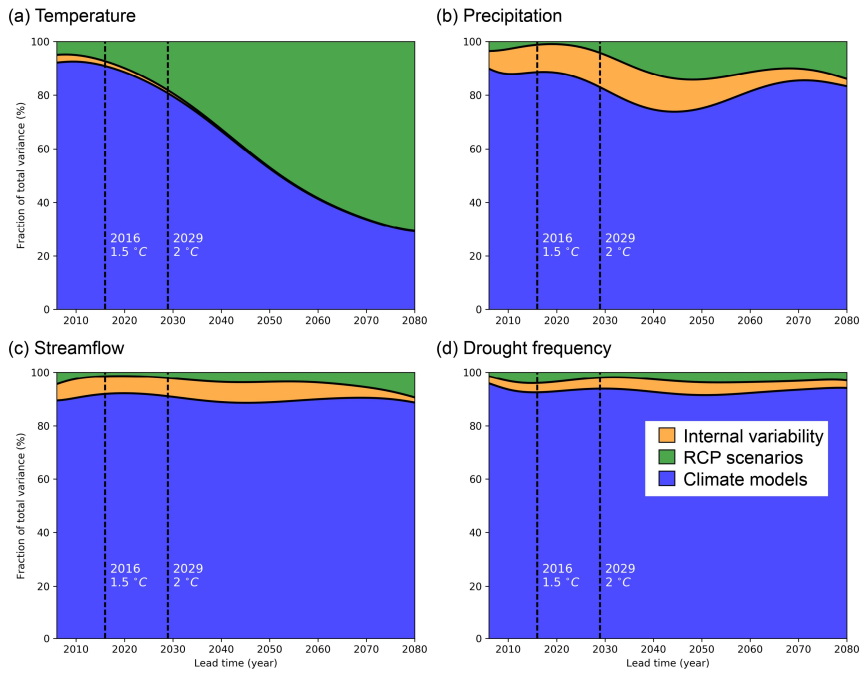

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GCMs	Institute	Resolution	Historical simulations	RCP scenarios
GFDL-CM3	NOAA GFDL	144×90	ALL	RCP2.6/4.5/6.0/8.5
GFDL-ESM2M	NOAA GFDL	144×90	ALL	RCP2.6/4.5/6.0/8.5
HadGEM2-ES	MOHC	192×145	ALL	RCP2.6/4.5/6.0/8.5
IPSL-CM5A-LR	IPSL	96×96	ALL	RCP2.6/4.5/6.0/8.5
IPSL-CM5A-MR	IPSL	144×143	ALL	RCP2.6/4.5/6.0/8.5
MIROC-ESM-CHEM	MIROC	128×64	ALL	RCP2.6/4.5/6.0/8.5
MIROC-ESM	MIROC	128×64	ALL	RCP2.6/4.5/6.0/8.5
MRI-CGCM3	MRI	320×160	ALL	RCP2.6/4.5/6.0/8.5

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Historical (1961-2005) and future (2006-2099) scenarios	**Changing trend of standardized timeseries (yr^{-1})**			
	Temperature	**Precipitation**	**Streamflow**	**Drought frequency**
(historical) observations	0.0494**	-0.0216*	-0.0503**	0.0448**
(historical) all forcings simulations	0.0272**	-0.0009	-0.0213**	0.0346**
(future) RCP2.6 simulations	0.0138**	0.0025*	0.0046**	-0.0069**
(future) RCP4.5 simulations	0.0291**	0.0056**	0.0105**	-0.0096**
(future) RCP6.0 simulations	0.0312**	0.0039**	0.0038**	-0.0044**
(future) RCP8.5 simulations	0.0345**	0.0108**	0.0133**	-0.0107**

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GCMs	1.5 °C warming level				2 °C warming level			
	RCP2.6	**RCP4.5**	**RCP6.0**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**
GFDL-CM3	2016	2016	2016	2016	2021	2016	2018	2016
GFDL-ESM2M	2031	2023	2030	2023	NR	2048	2064	2041
HadGEM2-ES	2016	2016	2016	2016	2020	2036	2023	2024
IPSL-CM5A-LR	2016	2018	2016	2016	2033	2028	2038	2026
IPSL-CM5A-MR	2016	2016	2016	2016	2037	2025	2033	2023
MIROC-ESM-CHEM	2016	2021	2016	2016	2022	2031	2032	2026
MIROC-ESM	2017	2017	2017	2017	2025	2029	2025	2023
MRI-CGCM3	2047	2028	2045	2024	NR	2049	2060	2040
Model ensemble	2016	2018	2016	2016	2029	2030	2033	2025
Total ensemble	2016				2029			

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Variables	1.5 °C warming level			2 °C warming level		
	Internal variability	Climate Models	RCPs scenarios	Internal variability	Climate Models	RCPs scenarios
Temperature	2.0	90.1	8.0	1.2	80.5	18.4
Precipitation	10.0	88.1	2.0	12.5	82.8	4.8
Streamflow	6.7	91.2	2.1	6.9	90.9	2.3
Drought frequency	3.4	93.3	3.3	4.1	93.4	2.5