CMIP6 projects less frequent seasonal soil moisture droughts over China in response to different warming levels

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Abstract
Seasonal drought occurrences are found to increase across different regions over China under global warming, but with large uncertainties among models. With ten selected Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models and seven CMIP6 models according to their performances in reproducing historical drought trends \(p < 0.1\), here we show that future seasonal soil moisture (SM) droughts over China projected by CMIP6 models are less frequent than that by CMIP5 models. We find national mean seasonal drought frequency is projected to increase by 28 ± 4% based on CMIP5 models at 1.5 °C global warming level, but only increase by 18 ± 6% based on CMIP6 models and 12 ± 4% based on land surface model ensemble simulations driven by downscaled CMIP5 models. Compared with CMIP6, CMIP5 projection suggests larger increase in precipitation but also larger increase in evapotranspiration, leading to more frequent seasonal SM droughts. Comparing the results at 3 °C global warming level with those at 1.5 °C, drought frequency over China will increase further by 10 ± 4%, but drought duration will decrease by 6 ± 4%, suggesting more frequent seasonal SM droughts with shorter durations will occur in a warming future. The future increase in China drought frequency will reduce from 12%–45% based on selected climate models to 3%–27% based on all available models (30 CMIP5 models and 31 CMIP6 models), which indicates that the model selection is critical for future drought projection. Nevertheless, CMIP6 still projects less frequent seasonal SM droughts than CMIP5 even without any model discriminations.

1. Introduction
Drought is a period with below-average precipitation (P) and/or above-normal evaporation, all of which reflected in the land surface with declined soil moisture (SM). Drought caused by such SM deficit is often referred to as agricultural drought, leading to reduced crop production and plant growth (Dai 2011, Li et al 2018). Due to its slow development, it is difficult to detect drought until it has caused devastating losses, bringing out famine, migration, and potential conflict (Berg and Sheffield 2018). In a warming future, droughts will become more frequently (Sheffield and Wood 2008, Dai 2013, Zhao and Dai 2015, Liu et al 2018, Samaniego et al 2018, Yuan et al 2019, Gu et al 2020), and approximately two thirds of global population will experience a progressive increase in drought conditions (Naumann et al 2018), leading to large economic losses, ecosystem damages and water shortages, and increasing the risk of wildfires and heatwaves.

The current rate of warming is too fast for the climate system to adapt to, leading to frequently occurred extreme events in recent years. As a result, the 2 °C warming level was first proposed in 1996 to avoid irreversible risk from climate extremes including droughts. The Copenhagen accord of 2009 explicitly accepted the 2 °C target. To further mitigate the impact of global warming, the 2015 Paris Agreement emphasized that ‘holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels’. Previous study suggests that the temperature
in China is expected to increase by 1.3 °C–5 °C by the end of this century, which is higher than the average warming level in the world (Chen and Sun 2015). Hence, it is necessary to assess China drought changes under different global warming levels.

A few studies focused on global drought changes under different warming levels, but their conclusions are not necessarily consistent over China. Based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) model outputs, Lehner et al. (2017) found that Palmer Drought Severity Index (PDSI) showed a non-significant decreasing (drying) trend over South China at the global warming levels of 1.5 °C and 2 °C, but Su et al. (2018) found that the PDSI showed a significant decreasing trend over South China and a significant increasing trend over North China. By using SM directly from the CMIP5 climate models, Lei et al. (2019) found that seasonal droughts over North China will increase at the warming level of 1.5 °C, although the mean SM will increase. A recent study from Cook et al. (2020) showed that the latest CMIP6 models projected a wetting SM condition over North China at the end of the 21st century, while the CMIP5 models projected a drying condition. Whether this affects the assessment of seasonal SM drought changes over China needs further investigation. In addition, many studies argued that SM from CMIP models might have large uncertainty due to the coarse resolution of climate models and simple representation of land surface processes, so they usually downscale climate output from CMIP models to drive advanced land surface models (LSMs) to provide more reliable estimation of SM, and assessed the corresponding changes in drought in the future (Samaniego et al. 2018, Yuan et al. 2019). Again, whether the CMIPs and LSMs combinations provide significantly different SM drought projection remains unknown.

Therefore, this work used SM from three sets of data, i.e. CMIP5 climate models, CMIP6 climate models, and a set of LSMs ensemble simulations driven by CMIP5 models (CMIP5/LSM), to project the future drought changes over China under 1.5 °C, 2 °C and 3 °C global warming scenarios separately, aiming to answer the following questions: (a) how will seasonal SM droughts change over China at 1.5 °C global warming level? (b) After exceeding 1.5 °C warming target, are there any significant changes in seasonal SM droughts under further warming (e.g. 2 °C and 3 °C warming levels)? (c) Compared with the results from CMIP5, do CMIP6 and CMIP5/LSM provide any new evidence regarding the drought changes over China?

2. Data and method

2.1. CMIP5 and CMIP6 data

In this work, we firstly compiled surface air temperature, P, evapotranspiration (ET), meridional wind at 850 hPa and total column SM data from 30 CMIP5 models for historical simulations (1961–2005) and future projections (2006–2099) under Representative Concentration Pathway 4.5 (RCP4.5) and RCP8.5 due to data availability (table S1). Given that the reference data (i.e. OBS/LSM, see section 2.2 for details) showed a significant increasing trend (p < 0.01) in national mean dry months (SM lower than 20th percentile) during 1961–2005, we finally chose ten CMIP5 models considering their ability (p < 0.1) to reproduce this upward trend (Top ten in table S1 and figure S1 (available online at stacks.iop.org/ERL/16/044053/mmedia)). Here, p < 0.1 instead of p < 0.01 was used to keep enough climate models for further analysis. As for the CMIP6 data, we compiled data from 31 climate models (table S2) for historical simulations (1961–2014) and future projections (2015–2100) under two Shared Society Pathways (i.e. SSP245 and SSP585). The SSP245 and SSP585 in CMIP6 future projections are corresponding to the scenarios of RCP4.5 and RCP8.5 in CMIP5 simulations, respectively. Based on the performance regarding the upward trend for historical droughts (p < 0.1), seven CMIP6 models were selected for further analysis (Top seven models in table S2 and figure S2). We used ALL experiments in historical simulations, which were forced by both natural (e.g. solar and volcanic activities) and anthropogenic (e.g. anthropogenic greenhouse gases and aerosol emissions) forcings. All data were interpolated to 0.5° bilinearly.

2.2. LSM ensemble simulations driven by observations and CMIP5 climate data

To assess the performance of simulating seasonal SM drought by using CMIP models, we used the benchmark data (OBS/LSM) provided by Yuan et al. (2019), where the meteorological observations were used to drive three LSMs (i.e. variable infiltration capacity (VIC; Xie et al. 2007), Noah LSM with multiple parameterization options (Noah-MP; Niu et al. 2011) and Community Land Model version 4.5 (CLM4.5; Oleson et al. 2013)) to simulate SM. These three models have good performance for hydrological simulations (Niu et al. 2011, Zong et al. 2011), and they have been widely used and verified.

Yuan et al. (2019) also selected 13 CMIP5 models, and bias corrected the simulated P and temperature through a quantile-mapping method (Wood et al. 2002) and an equal distance cumulative distribution function-matching method (Li et al. 2010) during historical and future periods, respectively. These bias-corrected P and temperature simulations were then used to drive the above three LSMs to provide SM simulations (Yuan et al. 2019), which are referred to as CMIP5/LSM in this study. Again, only CMIP5/LSM simulations that can capture the historical increasing trend (p < 0.1) of national mean dry months (SM lower than 20th percentile) were selected (table S3...
and figure S3). The difference between CMIP5 and CMIP5/LSM not only originates from the bias correction of meteorological forcings, but also the advances in three selected LSMs (i.e. VIC, Noah-MP, CLM4.5) for representing land surface hydrology.

2.3. Identification of different warming periods

The period 1971–2000 was selected to represent present-day conditions, and it corresponded to a global warming of 0.46 °C to pre-industrial conditions in 1881–1910 (Vautard et al 2014). Consequently, we used this period as the baseline period, and defined 1.5 °C, 2 °C and 3 °C global warming levels as the global surface air temperature increases by 1.04 °C (= 1.5 °C − 0.46 °C), 1.54 °C (= 2 °C − 0.46 °C), and 2.54 °C (= 3 °C − 0.46 °C) compared with the baseline period, respectively (Jiao and Yuan 2019). A 30 year moving window, which has the same length as the baseline period, was used to determine the first period reaching a specific warming level for a specific future scenario for CMIP5, CMIP5/LSM and CMIP6 simulations.

2.4. Definition of seasonal SM drought

SM is a key state variable of the land surface, reflecting complex interactions between the water, energy, and carbon cycles (Berg and Sheffield 2018). This work used the percentiles of SM to define drought (Andreadis et al 2005). According to this index, a seasonal drought event was defined as SM percentile below 20% for no less than three consecutive months (Yuan and Wood 2013). To characterize the seasonal drought event, frequency was calculated as the average number of seasonal drought events that occurred per year, duration was obtained by calculating the average months that drought events last, and the severity was the sum of deviation from 20% in percentiles averaged per events.

3. Results

The spatial distributions of frequency, duration and severity of seasonal SM droughts in the baseline period (1971–2000) are shown in figure S4. For each dataset, the drought characteristics of each model were calculated first and then averaged. Compared with OBS/LSM, it can be found that CMIP5/LSM simulates drought characteristics well, followed by CMIP6 and CMIP5 (figure S4). All datasets show a similar pattern where the frequency of seasonal droughts is higher over South China and lower over North and Northeast China (figures S4(a)–(d)). The patterns for the mean duration and severity are different from the drought frequency, where the droughts over North and Northeast China have longer durations and larger severity than those over South China (figures S4(e)–(l)). The results are consistent with Wang and Yuan (2018), where SM from reanalysis were used to estimate seasonal drought characteristics. In fact, South China is located in a humid region with a large climate variability, where seasonal droughts would occur more frequently but with shorter durations than those over North and Northeast China with semiarid and semi-humid climate.

With reasonable simulations of historical seasonal droughts, these CMIP models were used for future projections. Figure 1 shows the percentage changes of seasonal drought frequency under different warming levels as compared with the baseline period. With 1.5 °C warming, CMIP5 shows the largest area of drought frequency increase, followed by CMIP6 and CMIP5/LSM. All three datasets indicate that more seasonal droughts would occur over South China, with mixed changes over North and Northeast China (figures 1(a), (d) and (g)). This suggests that the seasonal drought-prone region (e.g. South China) will face increasing drought frequency in the future. In contrast to the CMIP6 results, CMIP5 not only predicts more seasonal drought over South China, but also over parts of the North China (figures 1(a)–(c)). For the changes in drought duration (figure S5) and severity (figure S6), there is no clear North-South contrast in the spatial distributions as the temperature increases.

Figure 2 shows the changes in drought frequency and duration averaged over China and three sub-regions (figure 1(g)). CMIP5 suggests that the frequency of seasonal SM drought over China will increase by 28 ± 4%, 31 ± 8% and 45 ± 13% at the warming levels of 1.5 °C, 2 °C and 3 °C. However, CMIP5/LSM suggests that the drought frequency will only increase by 12 ± 4%, 12 ± 4% and 20 ± 7% (figure 2(a)). The results from CMIP6 are between them, where the frequency will increase by 18 ± 6%, 19 ± 8% and 25 ± 11%. The mean results from three datasets suggest that the drought frequency over China will increase by 17 ± 3%, 18 ± 4% and 26 ± 7% at 1.5 °C, 2 °C and 3 °C global warming levels. The drought frequency increase projected by CMIP5 over China is 34%–56%, 38%–60% and 44%–55% more than CMIP5/LSM and CMIP6 under different warming levels. The seasonal drought durations averaged over China also have increasing trends, and CMIP5 projects larger changes again (figure 2(b)).

The changes in regional mean results are elusive as compared with the national mean results. For Northeast China (39°–54° N, 121°–135° E), both CMIP5 and CMIP6 show increases in drought frequency at 1.5 °C, 2 °C, 3 °C global warming levels, but CMIP5/LSM shows insignificant decreases (figure 2(c)). As the warming continues, the uncertainties of the changes increase for all datasets (figure 2(c)). All three datasets show significant increases in drought duration over Northeast China at different warming levels, except for CMIP5/LSM at 2 °C warming level (figure 2(d)). For North China (34°–42° N, 98°–121° E), both CMIP6 and
CMIP5 show increases in drought frequency at different warming levels (figure 2(e)), but CMIP5/LSM shows decreases (figure 2(e)). All three datasets show increases in drought duration at different warming levels over North China, but CMIP5 projects 46%–88% and 49%–66% more increases than CMIP5/LSM and CMIP6, respectively (figure 2(f)). For South China (21°–34° N, 98°–121° E), all three datasets project significant increases in both drought frequency and duration (figures 2(g) and (h)), which suggests that adaptation for short-term droughts is needed for humid regions. This is also consistent with Yuan et al. (2019), where South China shows a significant increase in flash droughts (with durations ranging from 15 to 60 d) in the warming future.

To better understand the differences between CMIP5 and the other two datasets, we investigated changes in P, ET, P surplus (P-ET) and SM at 1.5 °C warming level (figure 3). There are increases in P over Northeast and North China, with different magnitudes for different datasets (figures 3(a)–(c)). The changes in P-ET over part of North China from CMIP5 are opposite with that from CMIP5/LSM and CMIP6 (figures 3(g)–(i)), suggesting that ET modeling is quite different from different datasets (figures 3(d)–(f)). As a result, SM increases over part of North China based on CMIP5/LSM and CMIP6 data (figures 3(k) and (l)), leading to the decreases or relatively small increase in drought frequency. For South China, all three datasets project non-significant changes in P and ET, except for CMIP5/LSM with significant increases in ET (figures 3(a)–(f)). The P-ET and SM decrease over parts of South China for CMIP5 and CMIP5/LSM, while shows non-significant change for CMIP6 (figures 3(g)–(l)). Therefore, the reasons for the increases in drought frequency over South China are different among three datasets, where the decreases in P-ET (figures 3(g) and (h)) and the consequently decreased SM (figures 3(i) and (k)) are responsible for the drought increases for CMIP5 and CMIP5/LSM. But for CMIP6, the mean SM does not change significantly. To further explore the reason, we calculated the PDF of annual mean P, ET and SM percentile averaged over South China (figure S9). We find that the PDF of ET skews towards the right tail (figures S9(d)–(f)), while the SM percentile skews towards the left tail (figures S9(g)–(i)), indicating that SM dynamics instead of mean SM change might be related to the drought increase for CMIP6 over South China (figure 3(l)). The changes in these hydrometeorological variables at 2 °C warming level (figure S7) are similar to those at 1.5 °C (figure 3). The P increases at 3 °C warming level are more than at 1.5 °C warming level over most parts of China (figures S8(a)–(c)), but ET also increases (figures S8(d)–(f)).
Figure 2. Projected percentage changes (%) in seasonal soil moisture drought frequency (left column) and duration (right column) averaged over China and its three subregions as indicated in figure 1(g). The three subregions are Northeast China (39°–54° N, 121°–135° E), North China (34°–42° N, 98°–121° E) and South China (21°–34° N, 98°–121° E). The bars show 5%–95% uncertainties which were estimated by using bootstrapping for 1000 times.

Previous study illustrated that a further increase of 0.5 °C (global mean temperature rises from 1 °C to 1.5 °C with respect to the pre-industrial period) posed greater risk than the previous increase of 0.5 °C, and this ‘acceleration risk’ principle may also be present in the next 0.5 °C additional warming (global mean temperature rises from 1.5 °C to 2 °C relative to the pre-industrial period) (Hoegh-Guldberg et al 2019). Therefore, we compared changes in drought characteristics under 2 °C and 3 °C warming levels relative to those under 1.5 °C warming. For the average changes over China, drought frequency will increase with additional warming of 0.5 °C or 1.5 °C (figures 4(a) and (c)), but the change is not significant in CMIP5/LSM and CMIP6 for additional warming of 0.5 °C (figure 4(a)). Over Northeast and North China, all three datasets show that P-ET will increase with additional warming of 0.5 °C or 1.5 °C (figures S10(a)–(c) and (g)–(i)), with a smaller magnitude for
Figure 3. Projected percentage changes (%) in mean precipitation (P), evapotranspiration (ET), P surplus (P-ET) and soil moisture (SM) under 1.5 °C warming level relative to the reference period 1971–2000 (columns from left to right are for simulations from CMIP5, CMIP5/LSM and CMIP6 respectively). The dots indicate that at least 80% of models agree on sign of the changes.

CMIP5. As a result, most datasets project a decrease in both drought frequency and duration over Northeast and North China, although the changes are not necessarily significant (figure 4). For South China, all three datasets display a significant increasing trend in drought frequency (figures 4(a) and (c)), except for CMIP5/LSM at 0.5 °C additional warming (figure 4(a)). The changes in drought duration over South China with additional warming are not significant. With additional warming of 1.5 °C, drought frequency over China will increase by 10 ± 4%, and drought duration will decrease by 6 ± 4%, suggesting more frequent seasonal SM droughts with shorter durations will occur. However, the effects of holding temperature within 1.5 °C on seasonal SM droughts are regionally dependent with large uncertainties.

4. Summary and discussion

This study explores the responses of seasonal SM drought over China at different global warming levels by using three datasets. At 1.5 °C warming level, the average drought frequency over China will increase by 28 ± 4%, 12 ± 4% and 18 ± 6% based on CMIP5, CMIP5/LSM and CMIP6 datasets respectively. The increases in drought frequency are 31 ± 8%, 12 ± 4% and 19 ± 8% for 2 °C warming, and 45 ± 13%, 20 ± 7% and 25 ± 11% for 3 °C warming. Thus, holding the temperature at 1.5 °C has a positive effect on controlling seasonal SM droughts over China.

Compared with CMIP5/LSM and CMIP6, CMIP5 shows 34%–56%, 38%–60% and 44%–55% larger increases in drought frequency over China at 1.5 °C, 2 °C and 3 °C warming levels, which may be induced by larger increase in ET projected by CMIP5. The most significant increases in drought frequency and duration occur over South China, where the decrease in P-ET and the consequently decreased SM are responsible for the drought increases for CMIP5 and CMIP5/LSM, but SM dynamics might be related to the drought increase for CMIP6 because there is no significant changes in mean SM.
Given that East Asian summer monsoon (EASM) greatly affects the P (drought) over China, it is necessary to explore the change in EASM under global warming. Here we use the meridional wind at 850 hPa over East China (20°–40° N, 105°–120° E) to measure EASM (Jiang et al 2020), and find that both the selected ten CMIP5 model ensemble and the seven CMIP6 model ensemble show that EASM will be intensified in response to different warming levels (figure S11). A few studies have also shown that the circulation of EASM is intensified by global warming (Lee and Wang 2014, Chen and Bordoni 2016, Jin and Stan 2019, Park et al 2020). The enhancing monsoon will increase P over North China and decrease P over South China, which is also consistent with the P changes shown in figures 3(a) and (c). But figures 3(d) and (f) show that ET also increases over North China, which is not only caused by the increasing P, but also due to increasing atmospheric water demands with increasing temperature. Therefore, the relation between EASM and SM drought is complicated, where the changes in both P and ET are critical. Our results are consistent with previous studies, where they show that Asian monsoon region will expose to more frequent seasonal drought conditions despite the intensification of extreme rainfall events (Ha et al 2020). Figure S11 also shows that CMIP6 projected monsoon wind increase is a little larger than CMIP5, but again this does not necessarily suggest more rainfall or less drought, as the change in seasonal SM drought not only depends on the change in rainfall seasonality, but also the change in ET. In addition, the warming of the equatorial eastern Pacific can last from winter to spring-summer in the next year, resulting in an enhanced delay relationship between EASM and ENSO. Therefore, more droughts tend to occur in South China in the years associated with the summer of El Niño decay (Zhang and Zhou 2015).

In this study, we selected a subset of climate models according to their capability in reproducing historical increase in SM droughts over China. If all the available climate models were used for the analysis, the increase in drought would be reduced from 12%–45% to 3%–27% (figure S12). This is because when we mix the models that have positive responses (drought increase) to warming with those have negative (drought decrease) or insignificant responses, the signal would be heavily smoothed. Therefore, model selection is crucial for projecting drought in the future.

Given that the 1.5 °C global warming target will be reached in the near future, drought adaptation is dependent on whether there is significant response to additional warming (e.g. 2 °C or 3 °C warming levels). Our results show that drought frequency over China will increase by 10 ± 4% with additional warming of 1.5 °C, but drought duration will decrease by 6 ± 4%. The response is elusive over Northeast and

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**Figure 4.** Projected percentage changes in seasonal soil moisture drought frequency (left column) and duration (right column) with continuous warming of 0.5 °C (top row) and 1.5 °C (bottom row) as compared with 1.5 °C warming. The bars show 5%–95% uncertainties which were estimated by using bootstrapping for 1000 times.
North China (figure 4) due to large uncertainty in modeling P and land surface hydrological processes. However, it is found that South China, the hotspot of the future increase in seasonal SM droughts, will experience more frequent droughts but with shorter durations (figure 4), although the reduction in duration is not statistically significant. This is also consistent with the intensification of flash drought over South China (Yuan et al. 2019). Flash drought is regarded as a subseasonal drought with rapid onset, and it is also preferable over humid regions. This raises a challenge for drought early warning, where these short-term droughts are difficult to predict because of the absence of oceanic anomaly. Understanding of the interactions among droughts at different time scales (Yuan et al. 2020) would be an urgent need to interpret the projection of different types of droughts and to facilitate developing early warning systems.

In addition to the physical mechanism and early warning of droughts, future research should also concentrate on investigating the ecological and physiological feedback between drought and vegetation. Recently, a study has shown that early spring greening caused by warming can modulate the occurrence and magnitude of agricultural drought in summer, which is mainly due to the enhanced ET and thus the loss of SM. Moreover, this additional soil drying may further exacerbate summer heatwaves (Lian et al. 2020). Faster SM losses, on the other hand, trigger additional P by raising atmospheric humidity, and partially compensate the soil water deficit caused by early greening. But there exists another biophysical feedback, where the soil water deficit results in less incoming surface radiation and lower energy-controlled ET, which may inhibit cloud development and subsequent P. Besides, these interaction processes can also be amplified or diminished by teleconnection, where large scale atmospheric circulation redistributes P over downwind regions (Zeng et al. 2019). Unfortunately, the overall impacts of these processes are still unclear (Lian et al. 2020). Conversely, drought affected by soil water deficit and the consequent increase in summer extreme events may inhibit vegetation growth and ecosystem production, especially for the arid and semiarid ecosystems sensitive to summer water supply. Given that South China with humid climate and dense vegetation will experience more seasonal droughts in a warming future, whether the early greening due to CO₂ fertilization amplifies the drought condition by pumping more water from soil, or the reduction in vegetation stomatal conductance resulted from increased CO₂ concentration decreases ET and alleviates the drought condition (Ji et al. 2020), is a key question. Moreover, recent studies have shown that equilibrium climate sensitivity of the latest generation of CMIP6 is larger than CMIP5 models (Meehl et al. 2020, Zelinka et al. 2020), which means that CMIP6 models might be is more sensitive to the increase of CO₂. Thus, such physiological effect is elusive and may affect future drought projection at different warming levels (Dai et al. 2018).

**Data availability statement**

The CMIP data support the findings of this study are openly available (https://esgf-node.llnl.gov/search/cmip6/, https://esgf-node.llnl.gov/search/cmip5).

The data that support the findings of this study are available upon reasonable request from the authors.

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**References**

Andreadis K M et al 2005 Twentieth-century drought in the conterminous United States J. Hydrometeorol. 6 985–1001
Berg A and Sheffield J 2018 Climate change and drought: the soil moisture perspective Curr. Clim. Change Rep. 4 180–91
Chen H P and Sun J Q 2015 Changes in climate extreme events in China associated with warming Int. J. Climatol. 35 2735–51
Chen J and Bordoni S 2016 Early summer response of the East Asian summer monsoon to atmospheric CO₂ forcing and subsequent sea surface warming J. Clim. 29 5431–46
Cook B I, Mankin J S, Marvel K, Williams A P, Smerdon G E and Anchukaitis K J 2020 Twenty-first century drought projections in the CMIP6 forcing scenarios Earth’s Future 8 e2019EF001461
Dai A G 2011 Drought under global warming: a review Wiley Interdiscip. Rev. Clim. Change 2 45–65
Dai A G 2013 Increasing drought under global warming in observations and models Nat. Clim. Change 3 171
Dai A G, Zhao T and Chen J 2018 Climate change and drought: a precipitation and evaporation perspective Curr. Clim. Change Rep. 4 301–12
Gu L, Chen J, Yin J, Sullivan S C, Wang H-M, Guo S, Zhang L and Kim J-S 2020 Projected increases in magnitude and socioeconomic exposure of global droughts in 1.5 °C and 2 °C warmer climates Hydrol. Earth Syst. Sci. 24 451–72
Ha K, Moon S, Timmermann A and Kim D 2020 Future changes of summer monsoon characteristics and evaporative demand over Asia in CMIP6 simulations Geophys. Res. Lett. 47 e2020GL087492
Hoegh-Guldberg O et al 2019 The human imperative of stabilizing global climate change at 1.5 °C Science 365(6459) eaaw6974
Ji P, Yuan X, Ma F and Pan M 2020 Accelerated hydrological cycle over the Sanjiangyuan region induces more streamflow extremes at different global warming levels Hydrol. Earth Syst. Sci. 24 5439–51
Jiang D B, Hu D, Tian Z P and Lang X M 2020 Differences between CMIP6 and CMIP5 models in simulating climate over China and the East Asian monsoon Adv. Atmos. Sci. 37 1102–18

Jiao Y and Yuan X 2019 More severe hydrological drought events emerge at different warming levels over the Wudinghe watershed in northern China HydroL. Earth Syst. Sci. 23 621–35

Jin Y and Stan C 2019 Changes of East Asian summer monsoon due to tropical air-sea interactions induced by a global warming scenario Clim. Change 153 341–59

Lee J Y and Wang B 2014 Future change of global monsoon in the CMIP5 Clim. Dyn. 42 101–19

Lehner F, Coats S, Stocker T F, Pendergrass A G, Sanderson B M, Raible C C and Smerdon J E 2017 Projected drought risk in 1.5 °C and 2 °C warmer climates Geophys. Res. Lett. 44 7419–28

Lei X, Chen N C and Zhang X 2019 Global drought trends under 1.5 and 2 °C warming Int. J. Climatol. 39 2375–85

Li H B, Sheffield J and Wood E F 2010 Bias correction of monthly precipitation and temperature fields from Intergovernmental Panel on Climate Change AR4 models using equidistant quantile matching J. Geophys. Res. 115 D10101

Li Y H et al 2018 Mechanisms and early warning of drought disasters: an experimental drought meteorology research over China (DroughtEX_China) Bull. Am. Meteorol. Soc. 100 673–87

Lian X et al 2020 Summer soil drying exacerbated by earlier spring greening of northern vegetation Sci. Adv. 6 eaax0255

Liu W B, Sun F, Lim W H, Zhang J, Wang H, Shiogama H and Zhang Y 2018 Global drought and severe drought-affected populations in 1.5 °C and 2 °C warmer worlds Earth Syst. Dyn. 9 267–83

Meeth G A, Senior C A, Eyring V, Flato G, Lamarque J F, Stouffer R J, Taylor K E and Schlund M 2020 Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models Sci. Adv. 6 eaba1981

Naumann G, Allieri L, Wyser K, Mentaschi L, Betts R A, Carrao H, Spinoni J, Vogt J and Feyen L 2018 Global changes in drought conditions under different levels of warming Geophys. Res. Lett. 45 3285–96

Niu G-Y et al 2011 The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements J. Geophys. Res. 116 D12109

Oleson K W et al 2013 Technical description of version 4.5 of the community land model (CLM) Report No. NCAR/TN-503 + STR, 420 (Boulder, CO: National Center for Atmospheric Research)