ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Climate warming outweighs vegetation greening in intensifying flash droughts over China

To cite this article: Miao Zhang *et al* 2022 *Environ. Res. Lett.* **17** 054041

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
15 December 2021

REVISED
29 March 2022

ACCEPTED FOR PUBLICATION
25 April 2022

PUBLISHED
9 May 2022

LETTER

Climate warming outweighs vegetation greening in intensifying flash droughts over China

Miao Zhang[1,2], Xing Yuan[1,2,*], Jason A Otkin[3] and Peng Ji[1,2]

[1] Key Laboratory of Hydrometeorological Disaster Mechanism and Warning of Ministry of Water Resources, Nanjing University of Information Science and Technology, Nanjing 210044, People's Republic of China
[2] School of Hydrology and Water Resources, Nanjing University of Information Science and Technology, Nanjing 210044, People's Republic of China
[3] Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin-Madison, Madison, WI 53706, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: xyuan@nuist.edu.cn

Keywords: flash drought, global warming, land cover change, trend, attribution

Supplementary material for this article is available online

Abstract

The increasing occurrence of flash droughts with rapid onsets poses a great threat to food security and ecosystem productivity. While temporal trends in flash droughts have been extensively studied, the contributions of climate warming, vegetation greening, and the physiological effect of rising CO_2 to trends in flash drought characteristics remain unclear. Here we show there are significant increasing trends in flash drought frequency, duration, and intensity for most of China during 1961–2016. Warmer temperatures and vegetation greening increase evapotranspiration and decrease soil moisture, and explain 89% and 54% of the increasing frequency of flash drought respectively. Rising CO_2 concentrations reduce stomatal conductance, which acts to decelerate the increasing drought frequency trend by 18%, whereas the physiological effects of rising CO_2 on flash drought duration and intensity are smaller. Warming also outweighs vegetation greening for the increasing trends of flash drought duration and intensity over most of China, except North China. Our study highlights the role of climate warming in increasing the risk of flash droughts.

1. Introduction

Flash drought develops rapidly over subseasonal time scales (Otkin *et al* 2018, Yuan *et al* 2018a, 2019, Pendergrass *et al* 2020). It causes rapid depletion in soil moisture, thereby damaging ecosystems and increasing risks for water and food security (Hoerling *et al* 2014, Zhang and Yuan 2020, Hunt *et al* 2021). There have been many extreme flash drought events worldwide such as the U.S. Midwest drought in 2012 (Otkin *et al* 2016), the southern China drought in 2013 (Yuan *et al* 2015), the Russian drought in 2010 (Christian *et al* 2020), and the 2019 drought in Australia (Nguyen *et al* 2021), causing enormous economic and agricultural losses. With anthropogenic influence on climate change, the risk of flash drought is projected to increase (Yuan *et al* 2019, Noguera *et al* 2020, Christian *et al* 2021, Mishra *et al* 2021, Wang and Yuan 2021).

The rapid depletion of soil moisture during flash droughts is not only related to precipitation deficits but also to high temperatures driving more water loss from the land surface (Koster *et al* 2019). According to the sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), global surface temperature during 2000–2020 was 0.99 °C higher than 1850–1900. What is more, the increase in temperature over China is 1.3 °C–1.7 °C/century since 1900, which is much larger than 1 ± 0.06 °C/century of the global land mean temperature increase (Yan *et al* 2020). Additional warming caused by human activities has been shown to further increase the occurrence of drought (Chen and Sun 2017, Samaniego *et al* 2018, Ault 2020, Hari *et al* 2020). Zhang *et al* (2021) argued that there is a contrast in trends of different flash drought severities over the Gan river basin in China, where exceptional flash droughts decrease while moderate and severe flash droughts trend slightly upward. A recent study by Yuan *et al* (2019) found that anthropogenic climate change explained 77% of the upward trend in flash drought frequency over China. However, most studies have focused on the combined influence of multiple meteorological factors on drought (Chen and Sun 2017, Samaniego *et al* 2018), while climate warming and its associated impacts on drought processes have received less attention.

The development of flash drought is not only influenced by climate change, but might also be related to the change of the land surface condition. Vegetation greening would also alter the terrestrial water cycle and thus the propagation of flash droughts (Ukkola *et al* 2016, Zeng *et al* 2018, Piao *et al* 2020, Chen *et al* 2021). Vegetation controls the exchange of water between the atmosphere and the land, and greening increases water loss through transpiration from an expanded leaf area. Chen *et al* (2019a) found that China led the greening of the earth, accounting for 25% of the global increase in leaf area index (LAI) during the past two decades. Previous studies show that greening contributes more than half of the global evapotranspiration (ET) increase since the 1980s (Zhang *et al* 2016, Zeng *et al* 2018). Chen *et al* (2021) found that vegetation greening increases flash drought frequency over the U.S. through enhancing ET. On the other hand, the physiological effect of elevated CO_2 lowers stomatal conductance and reduces plant water use, thus increasing water use efficiency (Zhou *et al* 2017, Wang *et al* 2019) and decreasing ET loss (Ji *et al* 2020a). Plant response to rising CO_2 concentration partially offsets the drought severity (Burke 2011, Swann *et al* 2016). However, the effects of warming, vegetation greening, and the physiological effects of rising CO_2 concentration on drought vary among different regions, so it is necessary to consider these divergent effects in an integrated assessment framework.

Land surface models are widely used in studying the trend of flash droughts under climate change and land cover change at regional scalses (Chen *et al* 2021, Mishra *et al* 2021). This study aims to investigate the trends of frequency, duration, and intensity of flash droughts over China during 1961–2016. In particular, multiple numerical experiments through land surface modeling were conducted to separate the contributions of increasing temperature, vegetation greening, and the physiological effects of rising CO_2 to the changes in flash droughts.

2. Materials and methods

2.1. Data

The CRUNCEPv7 forcing data includes 6-hourly wind, specific humidity, surface pressure, downward shortwave radiation and downward longwave radiation with a spatial resolution of 0.5 degree. The meteorological forcing for driving the land surface model is the CRUNCEPv7 data during 1961–2016 (Viovy 2018). Here, we replaced the CRUNCEPv7 daily precipitation and temperature with CN05 gridded observational data provided by China Meteorological Administration. The spatial resolution of CN05 is 0.25 degree compiled from over 2400 observational meteorological stations, which was shown to be better than global products over China (Wu and Gao 2013). The daily precipitation and temperature from CN05 were downscaled to 6-hourly according to the diurnal cycle of precipitation and temperature data from CRUNCEPv7, but the daily mean values are the same as CN05 given its accuracy. In particular, CN05 daily total precipitation was disaggregated into 6-hourly according to the ratio of CRUNCEPv7 6-hourly precipitation data, and the daily temperature bias between CN05 and CRUNCEPv7 was added back into CRUNCEPv7 6-hourly temperature data. The historical CO_2 concentration as an input of the land surface model is the same as that of CMIP6 historical experiments (figure S1 available online at stacks.iop.org/ERL/17/054041/mmedia; Meinshausen *et al* 2017).

LAI in the land surface model is used to represent vegetation conditions and here simulations with dynamic and fixed LAI are used to disentangle the effects of vegetation greening on flash droughts. Vegetation greening influences the terrestrial water cycle with the interaction of the soil-vegetation-atmosphere continuum, thus the propagation of flash drought (Chen *et al* 2021). The monthly LAI dataset used here consisted of CMIP6 LAI datasets at spatial resolutions ranging from 1° to more than 2° during 1961–1980 (table S1) and remote sensing LAI from the Global Land Surface Satellite product (GLASS-AVHRR) at 0.05° during 1981–2016, which were all interpolated or aggregated to 30 km resolution. The LAI datasets from 37 CMIP6 models were validated against GLASS-AVHRR LAI over China during the overlapped period of 1981–2014, with the E3SM-1-1, E3SM-1-1-ECA, and EC-Earth3-Veg-LR models selected due to the same trend over China and most subregions with GLASS-AVHRR (table S2) and reasonable spatial climatology over China (figure S2). The systematic biases for these CMIP6 LAI datasets were removed at monthly scale using the trend-preserved bias correction method suggested by ISI-MIP (figure S3; Hempel *et al* 2013), and the ensemble mean LAI was used for land surface modeling.

2.2. Experiment design

Here we used the Conjunctive Surface-Subsurface Process model version 2 (CSSPv2; Yuan *et al* 2018b). The CSSPv2-simulated soil moisture, streamflow, and ET were evaluated against multi-source observations in China (Yuan *et al* 2018b, Ji *et al* 2021, Liu *et al* 2021b). CSSPv2 performed better than

Table 1. Information for the land surface model experiments performed during this study. In the control experiment (CTL), the meteorological forcings are from CRUNCEPv7 and CN05, and the CO_2 concentration and LAI vary year by year. Other experiments use detrended temperature at the pivot year of 1961 (Temp_min) or 2016 (Temp_max), fixed CO_2 concentration at 1961 (CO_2_min) or 2016 (CO_2_max), or fixed LAI at 1961 (LAI_min) or 2016 (LAI_max).

Name	Meteorological forcing	CO_2 concentration	LAI
CTL	CRUNCEPv7 and CN05	Dynamic	Dynamic
Temp_min	CRUNCEPv7 and CN05, but the trend of temperature is removed at the pivot of 1961	Dynamic	Dynamic
Temp_max	CRUNCEPv7 and CN05, but the trend of temperature is removed at the pivot of 2016	Dynamic	Dynamic
CO_2_min	CRUNCEPv7 and CN05	Fixed at 1961	Dynamic
CO_2_max	CRUNCEPv7 and CN05	Fixed at 2016	Dynamic
LAI_min	CRUNCEPv7 and CN05	Dynamic	Fixed at 1961
LAI_max	CRUNCEPv7 and CN05	Dynamic	Fixed at 2016

modern reanalysis for the simulation of daily soil moisture, with increased correlations of 26%–68% and reduced errors of 14%–24% validated against 2090 soil moisture observational stations in China (Zeng *et al* 2021). CSSPv2 was also successfully applied to simulate the effect of land cover change on hydrological processes and extremes over headwaters (Ji *et al* 2020a, 2020b). The study period is from 1961 to 2016 and the spatial resolution of these experiments is 30 km, with meteorological forcings and surface data mentioned above regridded to the same resolution.

The control experiment (CTL) was used to simulate the real situation. It was conducted by using observed meteorological forcing (CRUNCEPv7 and CN05), dynamic LAI from satellite observations and earth system model simulations, and dynamic CO_2 concentrations from observations. The six sensitivity experiments listed in table 1 used detrended temperature (Temp_min/Temp_max), fixed LAI (LAI_min/LAI_max), and fixed CO_2 concentration (CO_2_min/CO_2_max) to distinguish the influence of warming, vegetation greening, and the physiological effects of CO_2 concentration on flash drought trends relative to CTL. In the experiments of Temp_min and Temp_max, the seasonal trends for daily temperature were removed to exclude long-term trends but conserve the daily variability as follows:

$$\mathrm{Temp}_{adj,i,j} = \mathrm{Temp}_{i,j} + \alpha_j\left(i_{\mathrm{pivot}} - i\right), \quad (1)$$

where $\mathrm{Temp}_{i,j}$ is the real daily temperature in year i and season j, and $\mathrm{Temp}_{\mathrm{adj},i,j}$ is the adjusted daily temperature in the same year and season, where the linear trend of temperature at season j during 1961–2016 was removed. α_j is the linear trend in temperature in season j at a given grid cell, and i_{pivot} is the pivot year, which was chosen as 1961 in the experiment of Temp_min and 2016 in the experiment of Temp_max, representing cold and warm climate scenarios, respectively (Mao *et al* 2015). In the experiments of LAI_min and LAI_max, the monthly LAI was fixed in 1961 and 2016 respectively, and meteorological forcings and CO_2 concentrations are the same as those in CTL experiment with interannual variations and long-term trends. In a similar way, the annual time series of CO_2 concentrations were fixed in 1961 and 2016 in CO_2_min and CO_2_max, respectively, and meteorological forcings and LAI are the same as those in CTL.

2.3. Attribution of trends in flash drought characteristics

Firstly, we identified flash droughts using soil moisture from CSSPv2 simulations as listed in table 1. The soil moisture averaged from the surface to the depth of 1 m was transformed into soil moisture percentiles at pentad scale, and the flash drought event was identified according to Yuan *et al* (2019). For a flash drought to occur, the soil moisture percentiles must drop from above the 40th percentile to below the 20th percentile with the decline rate of soil moisture percentiles being no less than 5% per pentad. The flash drought ends when the soil moisture percentile subsequently recovers above the 20th percentile. The duration of flash drought is the total period from the onset (drops below the 40th percentile) to the end of flash drought (recovers up to the 20th percentile). The intensity of the flash drought is calculated as the mean deficit of soil moisture percentiles per pentad compared with the threshold of 40% during the entire flash drought event. Considering the ecological impacts of flash droughts, we only focus on the growing season from April to September. Then, the contributions of warming, vegetation greening, and increasing CO_2 to flash droughts were obtained by comparing results from CTL to each of the sensitivity experiments (Piao *et al* 2015). The contributions of each factor to the trend of flash drought frequency, duration, and intensity were calculated as follows:

$$\mathrm{trend}_{\alpha,\beta} = \frac{\mathrm{trend}_{CTL-\exp 1,\beta} + \mathrm{trend}_{CTL-\exp 2,\beta}}{2}, \quad (2)$$

where $\mathrm{trend}_{CTL-\exp 1,\beta}$ and $\mathrm{trend}_{CTL-\exp 2,\beta}$ are the linear trends of differences for a certain flash drought characteristic β (i.e. frequency, duration, or intensity) between CTL and a sensitivity experiment, respectively. The $\mathrm{trend}_{\alpha,\beta}$ is the contribution of the factor

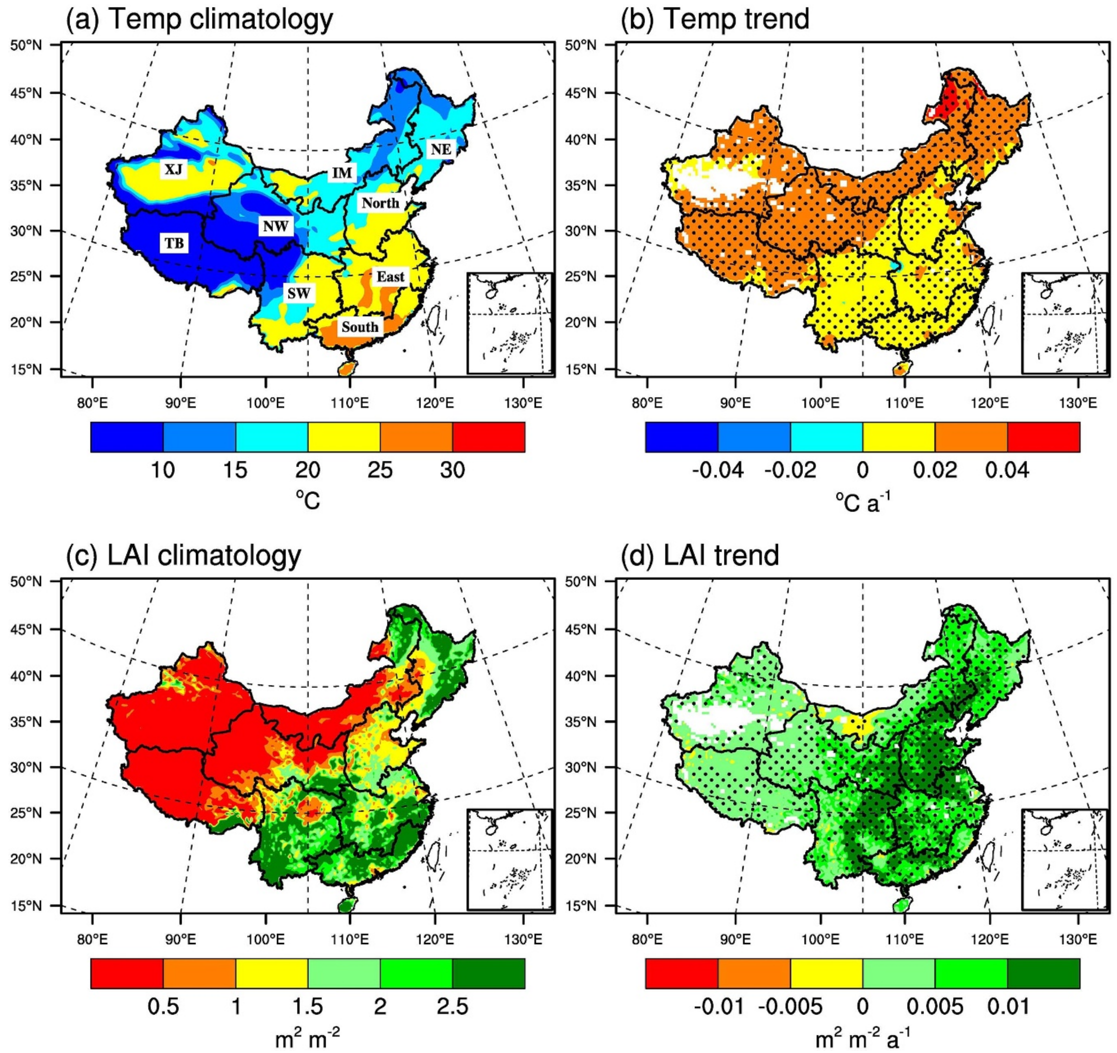

Figure 1. The climatology and linear trends of growing season temperature (°C) and leaf area index (LAI, m^2 m^{-2}) during 1961–2016. Stippling over each pixel indicates a 95% confidence level. There are nine subregions (a): northeastern China (NE), Inner Mongolia (IM), northern China (North), northwestern China (NW), Xin Jiang (XJ), Tibet (TB), southwestern China (SW), eastern China (East), and southern China (South).

α which is set in exp1 and exp2 to the trend of flash drought characteristic β. The significance of linear trends was evaluated using Student-t test with a 95% confidence level. If the values of $\text{trend}_{\text{CTL}-\text{exp1},\beta}$ and $\text{trend}_{\text{CTL}-\text{exp2},\beta}$ are both positive or negative, and at least one of them is statistically significant, the contribution of the factor α to the trend of flash drought is considered statistically significant. China is divided into nine regions including northeastern China, Inner Mongolia, northern China, northwestern China, Xin Jiang, Tibet, southwestern China, eastern China, and southern China as shown in figure 1(a). Xin Jiang is excluded in the analysis considering the limited occurrences of flash droughts (figure S4(a)).

3. Results and discussions

3.1. The trend of temperature, LAI, and CO_2 concentration over China

Figure S4 shows the multi-year mean frequency, duration, and intensity of flash droughts during 1961–2016 based on CSSPv2 simulation. The mean frequency, duration, and intensity of flash droughts averaged over China are 2.5 events/decade, 47.6 d/event, and 23.6% percentile/pentad, respectively. The multi-year mean temperature during growing seasons is relatively high over southern and eastern China (>20 °C) and low over Tibet and northwestern China (<10 °C; figure 1(a)). Warming is expected to intensify droughts through increasing atmospheric evaporative demand (Cook et al 2014, Trenberth et al 2014, Grossiord et al 2020). In China, the growing season temperature is significantly increasing at 0.02 °C per year ($p < 0.001$), and the trend is larger over Tibet, northwestern China, Inner Mongolia, and northeastern China (figure 1(b)), which is consistent with Sun and Ao (2013), Hu and Sun (2021), and Huang et al (2022). Figure 1(c) shows the spatial climatology of growing season LAI during 1961–2016, which is higher over southern, southwestern, eastern, and northeastern China. Climate change and CO_2 fertilization are dominant drivers of vegetation greening on a global scale (Piao et al 2020). Besides, a series of projects to conserve and expand forests have been conducted over China since the 2000s. The LAI shows a significant increasing trend at 0.87 m^2 m^{-2} per year ($p < 0.001$) over China, with a larger increasing rate over northern and northwestern China (figure 1(d)). Although droughts cause vegetation browning or even plant mortality during a dry period, they still do not change the long-term increasing trend of LAI. The CO_2 concentrations also show a significant upward trend during 1961–2016 (figure S1).

3.2. Attribution of the trend of flash drought characteristics

The mean frequency of flash droughts averaged over China is 2.9 events/decade, 2.5 events/decade, and 3.4 events/decade in experiments with high values of LAI (LAI_max), CO_2 concentration (CO_2_max), and temperature (Temp_max), respectively. Flash drought frequency is increased due to higher LAI and temperature as compared with 2.5 events/decade in CTL experiment. Figure 2 shows the trends of flash drought frequency, duration, and intensity over China and its subregions simulated by the CTL experiment that includes observed warming, increases in LAI, and the physiological effects of increasing CO_2 concentration, and those simulated by sensitivity experiments where the CO_2 concentration, LAI, or temperature are detrended respectively. In the CTL experiment, the trend for the frequency of flash droughts averaged over China is 0.016 events per decade per grid point ($p < 0.1$), concentrated over northern China, northeastern China, and Inner Mongolia (figure 2(a)). The frequency of flash drought increases by 39% from 1961 to 2016. The duration of flash drought events increased at 1.1, 3.3, 0.9 and 2.4 d per decade over northern China, southwestern China, Inner Mongolia and Tibet, whereas the trend of the duration is −2.2 d per decade over northwestern China (figure 2(b)). The trend of intensity is similar to the trend of duration, which is positive over northern and northeastern China, Inner Mongolia and Tibet and negative over northwestern China (figure 2(c)).

In the experiments of CO_2_min and CO_2_max, the influence of rising CO_2 concentration on flash droughts is ignored and the average mean of trends of flash drought characteristics in CO_2_min and CO_2_max is used here, which are only under the influence of climate warming and vegetation greening. The increase in flash drought frequency over China is larger when the CO_2 concentration is fixed (blue boxes compared with black boxes, figure 2(a)). Thus increasing CO_2 concentrations decreases the trend of flash drought frequency by 0.003 events per decade, which partially offsets (18%) the overall increase in flash droughts in CTL. Rising atmospheric CO_2 decreases stomatal conductance, thus decreasing evapotranspiration during droughts. The CO_2 physiological effects alleviate the increasing trend of flash drought frequency by 6%, 13%, and 8% over northern China, northeastern China, and Inner Mongolia, respectively. The influence of CO_2 physiological effects on soil moisture is most significant over northeastern China, with the largest increase in soil moisture induced by higher CO_2 concentrations (>0.003 m^3 m^{-3} per 100 ppm CO_2; figure S6(c)). However, the effects of rising CO_2 on the hydrological cycle are rarely considered, which may overestimate the risk of drought in climate change (Liu et al 2021a).

When there is no warming in the experiments of Temp_max and Temp_min, the trend of flash drought frequency averaged over China is only 0.002 events per decade (red boxes, figure 2(a)), which is much lower than that in a warming climate (CTL experiment). The contribution of increasing temperature is 89% to the increasing trend of flash drought frequency over China. The trend of flash drought frequency without warming is 0.04, 0.03, and 0.04 events/decade over northern China, northeastern China, and Inner Mongolia; therefore, climate warming accounts for 6%, 55%, and 37% of the increasing flash drought frequency over these regions, respectively. Climate warming explains more of the increasing flash drought frequency over northeastern China than northern China as their soil moisture is more sensitive to the change of temperature (figure S6(b)). What is more, the magnitudes of the increases in temperature over northeastern China and Inner Mongolia are also higher (figure 1(b)). The change of flash drought frequency induced by warming over eastern China is also significant (figure 2(a)).

Vegetation greening generally intensifies flash drought, and accounts for the increasing trend of flash drought frequency by 54%, 49%, 21% and 34% over China, northern China, northeastern China and Inner Mongolia, respectively (green boxes compared with black boxes, figure 2(a)). Overall, both warming and vegetation greening contribute to the increase in flash drought frequency, and the increase in temperature plays a more important role than vegetation greening, whereas the CO_2 physiological effects alleviate the increasing trend of flash drought frequency. For northern China, the increase in LAI contributes more than warming to the increasing flash drought events. However, for northeastern China, climate warming plays a more important role in increasing flash droughts.

The warming and vegetation greening also contribute to the increases in flash drought duration and intensity (figures 2(b) and (c)). The regions with a longer duration of flash droughts including northern

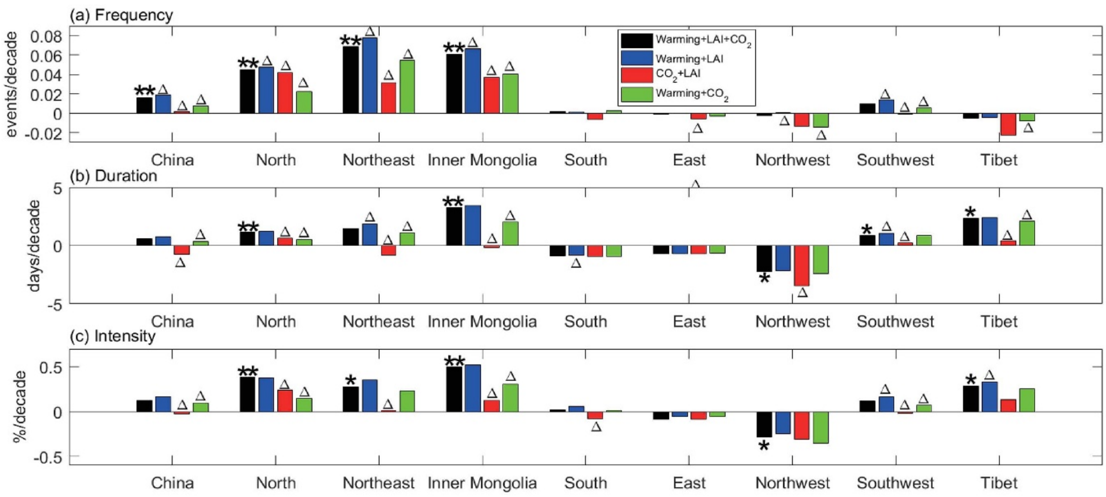

Figure 2. Linear trends of flash drought frequency, duration, and intensity during 1961–2016 over China and eight sub-regions considering different factors including climate warming, vegetation greening, and increasing CO_2 concentration. ** and * show that the trend is statistically significant at the 95% and 90% confidence levels in the control experiment respectively, and the triangle indicates that the difference for a given flash drought characteristic is significant at a 95% confidence level between the control experiment and the sensitivity experiments that exclude dynamic CO_2 concentration, climate warming, or vegetation greening.

China, Inner Mongolia, southwestern China, and Tibet are mainly attributed to increases in temperature, with the contributions ranging from 76% to 104%. For northern China, warming and vegetation greening account for 45% and 56% of the increase in flash drought duration, and 15% and 37% of the increase in flash drought intensity, respectively. And the warming also accounts for 95% and 75% of the increasing intensity of flash droughts over northeastern China and Inner Mongolia, respectively. The flash drought duration and intensity over northwestern China show decreasing trends, which are probably influenced by increasing soil moisture since the 2000s (figure S5(g)). What is more, warming has a larger influence on the duration and intensity of flash drought than on their frequency, which implies that flash droughts are stronger and last longer under higher temperature.

3.3. The influences of vegetation greening, warming, and CO_2 physiological effects on the water cycle

Here we explain the spatially divergent changes of flash drought over China from the water cycle perspective under a changing environment. Figure 3 shows changes in the trends in soil moisture, evapotranspiration, and total runoff due to increasing LAI, temperature, and CO_2 concentration. The soil moisture generally decreases due to increasing LAI and climate warming, whereas the soil moisture increases as CO_2 concentration increases. Soil moisture decreases are larger due to increasing LAI than to climate warming over northern China (figures 3(a) and (b)), which may be related to larger trends of LAI and a higher sensitivity of hydrological intensification to LAI compared with other regions (figures 1(d) and S6(a); Deng *et al* 2020). In contrast, warming plays a more important role in decreasing soil moisture over northeastern China. This is consistent with the above findings that the increasing trend in LAI explains most of the intensified flash droughts over northern China, while climate warming accounts for more of the increasing flash droughts over northeastern China. The magnitude of the change of soil moisture due to increasing CO_2 concentration is smaller than that induced by climate warming and vegetation greening. The increasing LAI is expected to increase vegetation transpiration (Zeng *et al* 2017, Li *et al* 2018), and the linear trend of ET change due to increasing LAI is generally positive, especially over northern China (figure 3(d)). Correspondingly, total runoff decreases due to increasing LAI and ET (figure 3(g)). Warming also enhances ET (figure 3(e)) and decreases the total runoff (figure 3(h)) over China. The soil moisture change induced by warming is regulated by the change of ET and runoff. The trend of soil moisture change induced by increases in LAI is not significant over southern China and eastern China (figures 3 and S6(a)), thus the greening vegetation may not intensity flash drought over these regions. This result is consistent with that greening has more obvious effects on the hydrological cycle over relatively dry regions than wet regions (Zeng *et al* 2018). Higher CO_2 concentration results in stomatal closure and decreases stomatal conductance, thus the ET change induced by high CO_2 concentration shows a decreasing trend (figure 3(f)), and the runoff is increased (figure 3(i)).

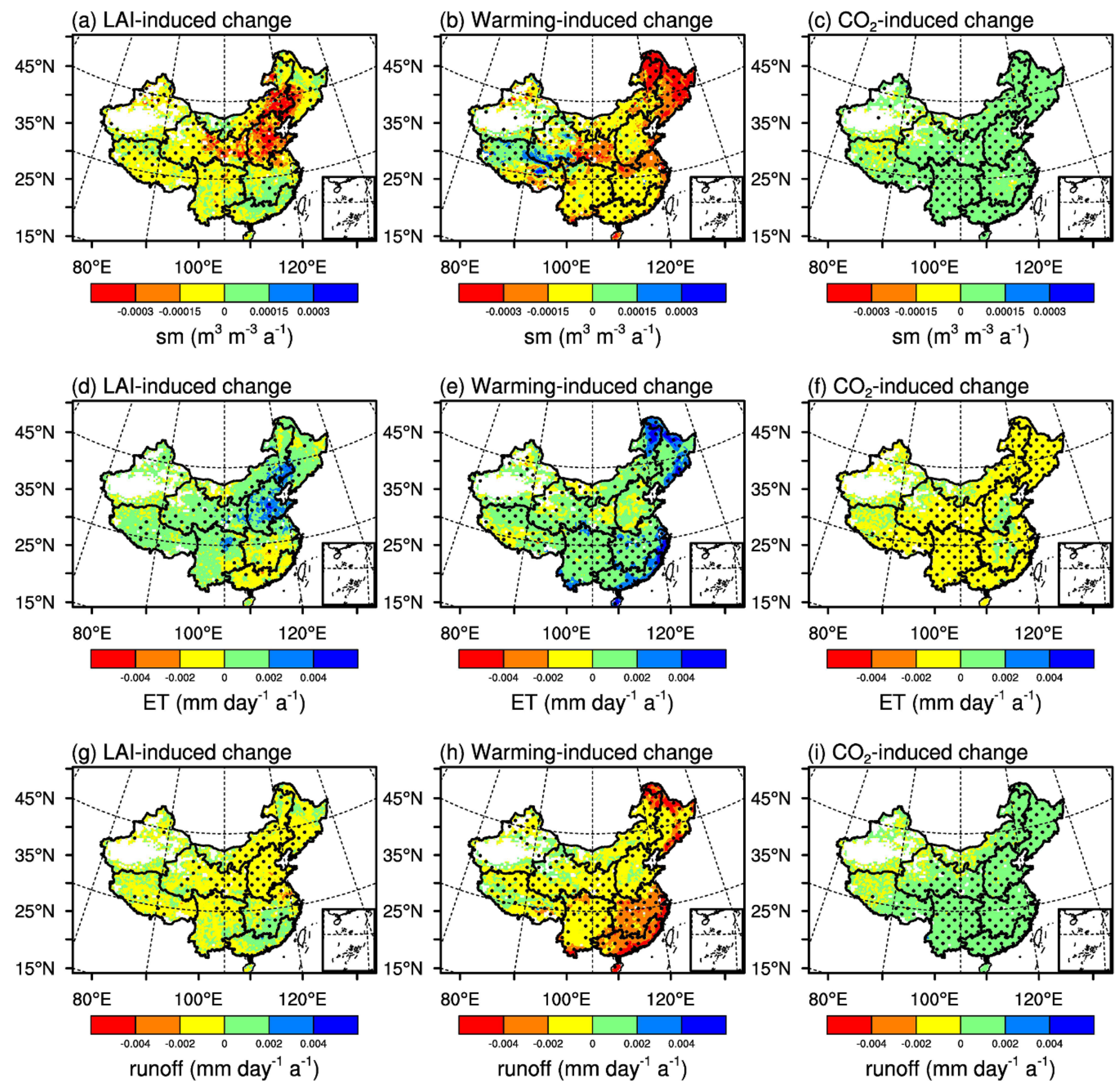

Figure 3. Linear trends of changes in soil moisture, evapotranspiration, and runoff induced by vegetation greening (a), (d) and (g), climate warming (b), (e), (h), and increasing CO_2 concentration (c), (f) and (i).

4. Conclusions

This study investigates trends in flash drought frequency, duration, and intensity over China during 1961–2016, and examines the role of increasing temperature, vegetation greening, and elevated atmospheric CO_2 concentration on these trends through land surface modeling. Flash droughts have become more intense over northern China, northeastern China, Inner Mongolia, and Tibet. In northwestern China, the trends of flash drought duration and intensity are decreasing which may be related to a wetter trend. Previous studies have focused on the influence of climate and vegetation change on a certain hydrological variable, whereas the attribution of drought has received less attention. What is more, the dominant role of climate and land cover change in intensifying water cycle is different in each region (Zhang *et al* 2008, Ji and Yuan 2018, Chen *et al* 2019b). Through performing sensitivity simulations with a land surface model, the effects of climate warming, vegetation greening, and plant physiological response to rising CO_2 on flash droughts are separated. Over all of China, warming, vegetation greening, and increasing CO_2 concentration account for 89%, 53%, and −18% of the increasing flash drought frequency. Warming is more important than vegetation greening in intensifying flash droughts over northeastern China, Inner Mongolia, southwestern China, and Tibet. Increasing LAI accounts for 49%, 55% and 61% of the trends of flash drought frequency, duration and intensity over northern China. Increasing LAI induces larger deficits in soil moisture over northern China than other regions, which is consistent with the key role of vegetation greening in intensifying flash droughts. The decrease in soil moisture caused by warming is larger than greening over northeastern China, thus the influence of warming on flash droughts is dominant. The CO_2 physiological effects are more consistent over China, that is, higher CO_2 concentration results in wetter soils and larger runoff and decreases in ET. However, the compensatory effects of rising CO_2 on flash droughts are still lower than the intensification effects of warming and vegetation greening.

There are obvious signatures of warming, vegetation greening, and increasing atmospheric CO_2 concentration over the globe (Li *et al* 2018, Zeng *et al* 2018, Chen *et al* 2019a, IPCC 2021), and this study investigates the relative role in the trends of flash drought characteristics, which can also offer guidelines to other regions around the world. The response of flash droughts to warming and vegetation greening varies over China and is influenced by the sensitivity of the hydrological cycle to different factors. The larger influence of increasing temperature on flash drought duration and intensity implies the key role of temperature during the propagation of flash droughts. However, the above factors may not fully explain the trends of flash drought characteristics (<100%) or may over-explain the trends (>100%). The over-explanation of warming, vegetation greening, and rising CO_2 concentration for the trend of flash droughts may be related to the covariance among these factors, as LAI is also influenced by temperature (Piao *et al* 2020). On the other hand, here we only focus on the trend of temperature, while the trends of other climate variables need to be investigated in future studies.

Data availability statement

The meteorological forcing is derived from CRUNCEP available at https://svn-ccsm-inputdata.cgd.ucar.edu/trunk/inputdata/atm/datm7/. CMIP6 LAI datasets are downloaded from https://esgf-node.llnl.gov/search/cmip6/.

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

Acknowledgments

This work was supported by Natural Science Foundation of Jiangsu Province for Distinguished Young Scholars (BK20211540), National Natural Science Foundation of China (41875105), and National Key R&D Program of China (2018YFA0606002).

Conflict of interest

The authors declare no conflicts of interest relevant to this study.

ORCID iDs

Miao Zhang https://orcid.org/0000-0001-9714-5932
Xing Yuan https://orcid.org/0000-0001-6983-7368
Jason A Otkin https://orcid.org/0000-0003-4034-7845
Peng Ji https://orcid.org/0000-0002-4390-2114

References

Ault T R 2020 On the essentials of drought in a changing climate *Science* **368** 256–60
Burke E J 2011 Understanding the sensitivity of different drought metrics to the drivers of drought under increased atmospheric CO_2 *J. Hydrometeorol.* **12** 1378–94
Chen C *et al* 2019a China and India lead in greening of the world through land-use management *Nat. Sustain.* **2** 122–9
Chen H and Sun J 2017 Anthropogenic warming has caused hot droughts more frequently in China *J. Hydrol.* **544** 306–18
Chen L, Ford T W and Yadav P 2021 The role of vegetation in flash drought occurrence: a sensitivity study using community earth system model, version 2 *J. Hydrometeorol.* **22** 845–57
Chen Q, Chen H, Zhang J, Hou Y, Shen M, Chen J and Xu C 2019b Impacts of climate change and LULC change on runoff in the Jinsha River Basin *Water* **11** 1398
Christian J I, Basara J B, Hunt E D, Otkin J A, Furtado J C, Mishra V, Xiao X and Randall R M 2021 Global distribution, trends, and drivers of flash drought occurrence *Nat. Commun.* **12** 1–11
Christian J I, Basara J B, Hunt E D, Otkin J A and Xiao X 2020 Flash drought development and cascading impacts associated with the 2010 Russian heatwave *Environ. Res. Lett.* **15** 094078
Cook B I, Smerdon J E, Seager R and Coats S 2014 Global warming and 21st century drying *Clim. Dyn.* **43** 2607–27
Deng Y *et al* 2020 Vegetation greening intensified soil drying in some semi-arid and arid areas of the world *Agric. For. Meteorol.* **292–293** 108103
Grossiord C, Buckley T N, Cernusak L A, Novick K A, Poulter B, Siegwolf R T W, Sperry J S and McDowell N G 2020 Plant responses to rising vapor pressure deficit *New Phytol.* **226** 1550–66
Hari V, Rakovec O, Markonis Y, Hanel M and Kumar R 2020 Increased future occurrences of the exceptional 2018–2019 Central European drought under global warming *Sci. Rep.* **10** 1–10
Hempel S, Frieler K, Warszawski L, Schewe J and Piontek F 2013 A trend-preserving bias correction -the ISI-MIP approach *Earth Syst. Dyn.* **4** 219–36
Hoerling M, Eischeid J, Kumar A, Leung R, Mariotti A, Mo K, Schubert S and Seager R 2014 Causes and predictability of the 2012 great plains drought *Bull. Am. Meteorol. Soc.* **95** 269–82
Hu T and Sun Y 2021 Anthropogenic influence on extreme temperatures in China based on CMIP6 models *Int. J. Climatol.* **42** 1–15
Huang Y, Lu C, Lei Y, Su Y, Su Y and Wang Z 2022 Spatio-temporal variations of temperature and precipitation during 1951–2019 in Arid and Semiarid region, China *Chin. Geogr. Sci.* **32** 285–301
Hunt E *et al* 2021 Agricultural and food security impacts from the 2010 Russia flash drought *Weather Clim. Extremes* **34** 100383
IPCC 2021 *Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press) accepted
Ji P and Yuan X 2018 High-resolution land surface modeling of hydrological changes over the Sanjiangyuan region in the eastern Tibetan Plateau: 2. Impact of climate and land cover change *J. Adv. Model. Earth Syst.* **10** 2829–43
Ji P, Yuan X, Jiao Y, Wang C, Han S and Shi C 2020b Anthropogenic contributions to the 2018 extreme flooding over the upper Yellow River basin in China *Bull. Am. Meteorol. Soc.* **101** S89–S94

Ji P, Yuan X, Liang X Z, Jiao Y, Zhou Y and Liu Z 2021 High-resolution land surface modeling of the effect of long-term urbanization on hydrothermal changes over Beijing metropolitan area *J. Geophys. Res. Atmos.* **126** e2021JD034787

Ji P, Yuan X, Ma F and Pan M 2020a Accelerated hydrological cycle over the Sanjiangyuan region induces more streamflow extremes at different global warming levels *Hydrol. Earth Syst. Sci.* **1–33** 5439–51

Koster R D, Schubert S D, Wang H, Mahanama S P and DeAngelis A M 2019 Flash drought as captured by reanalysis data: disentangling the contributions of precipitation deficit and excess evapotranspiration *J. Hydrometeorol.* **20** 1241–58

Li Y *et al* 2018 Divergent hydrological response to large-scale afforestation and vegetation greening in China *Sci. Adv.* **4** 1–10

Liu J *et al* 2021a Response of global land evapotranspiration to climate change, elevated CO_2, and land use change *Agric. For. Meteorol.* **311** 108663

Liu J, Yuan X, Zeng J, Jiao Y, Li Y, Zhong L and Yao L 2021b Ensemble streamflow forecasting over a cascade reservoir catchment with integrated hydrometeorological modeling and machine learning *Hydrol. Earth Syst. Sci.* **26** 265–78

Mao Y, Nijssen B and Lettenmaier D P 2015 Is climate change implicated in the 2013–2014 California drought? A hydrologic perspective *Geophys. Res. Lett.* **42** 2805–13

Meinshausen M *et al* 2017 Historical greenhouse gas concentrations for climate modelling (CMIP6) *Geosci. Model Dev.* **10** 2057–116

Mishra V, Aadhar S and Mahto S S 2021 Anthropogenic warming and intraseasonal summer monsoon variability amplify the risk of future flash droughts in India *npj Clim. Atmos. Sci.* **4** 1–10

Nguyen H, Wheeler M C, Hendon H H, Lim E P and Otkin J A 2021 The 2019 flash droughts in subtropical eastern Australia and their association with large-scale climate drivers *Weather Clim. Extremes* **32** 100321

Noguera I, Domínguez-Castro F and Vicente-Serrano S M 2020 Characteristics and trends of flash droughts in Spain, 1961–2018 *Ann. New York Acad. Sci.* **1472** 155–72

Otkin J A, Anderson M C, Hain C, Svoboda M, Johnson D, Mueller R, Tadesse T, Wardlow B and Brown J 2016 Assessing the evolution of soil moisture and vegetation conditions during the 2012 United States flash drought *Agric. For. Meteorol.* **218–219** 230–42

Otkin J A, Svoboda M, Hunt E D, Ford T W, Anderson M C, Hain C and Basara J B 2018 Flash droughts: a review and assessment of the challenges imposed by rapid-onset droughts in the United States *Bull. Am. Meteorol. Soc.* **99** 911–9

Pendergrass A G *et al* 2020 Flash droughts present a new challenge for subseasonal-to-seasonal prediction *Nat. Clim. Change* **10** 191–9

Piao S *et al* 2015 Detection and attribution of vegetation greening trend in China over the last 30 years *Glob. Change Biol.* **21** 1601–9

Piao S *et al* 2020 Characteristics, drivers and feedbacks of global greening *Nat. Rev. Earth Environ.* **1** 14–27

Samaniego L, Thober S, Kumar R, Wanders N, Rakovec O, Pan M, Zink M, Sheffield J, Wood E F and Marx A 2018 Anthropogenic warming exacerbates European soil moisture droughts *Nat. Clim. Change* **8** 421–6

Sun J Q and Ao J 2013 Changes in precipitation and extreme precipitation in a warming environment in China *Chin. Sci. Bull.* **58** 1395–401

Swann A L S, Hoffman F M, Koven C D and Randerson J T 2016 Plant responses to increasing CO_2 reduce estimates of climate impacts on drought severity *Proc. Natl Acad. Sci. USA* **113** 10019–1002

Trenberth K E, Dai A, Van Der Schrier G, Jones P D, Barichivich J, Briffa K R and Sheffield J 2014 Global warming and changes in drought *Nat. Clim. Change* **4** 17–22

Ukkola A M, Prentice I C, Keenan T F, Van Dijk A I J M, Viney N R, Myneni R B and Bi J 2016 Reduced streamflow in water-stressed climates consistent with CO_2 effects on vegetation *Nat. Clim. Change* **6** 75–78

Viovy N 2018 CRUNCEP version 7—atmospheric forcing data for the community land model. research data archive at the national center for atmospheric research *Comput. Inf. Syst. Lab.*

Wang Y, Sperry J S, Venturas M D, Trugman A T, Love D M and Anderegg W R L 2019 The stomatal response to rising CO2 concentration and drought is predicted by a hydraulic trait-based optimization model *Tree Physiol.* **39** 1416–27

Wang Y and Yuan X 2021 Anthropogenic speeding up of south china flash droughts as exemplified by the 2019 summer-autumn transition season geophysical research letters *Geophys. Res. Lett.* **48** e2020GL091901

Wu J and Gao X 2013 A gridded daily observation dataset over China region and comparison with the other datasets *Chin. J. Geophys.* **56** 1102–11

Yan Z, Ding Y, Zhai P, Song L, Cao L and Li Z 2020 Re-assessing climate warming in China since the last century *Acta Meteorol. Sin.* **78** 370–8

Yuan X, Ji P, Wang L, Liang X Z, Yang K, Ye A, Su Z and Wen J 2018b High-resolution land surface modeling of hydrological changes over the Sanjiangyuan region in the eastern Tibetan Plateau: 1. Model development and evaluation *J. Adv. Model. Earth Syst.* **10** 2806–28

Yuan X, Ma Z, Pan M and Shi C 2015 Microwave remote sensing of flash droughts during crop growing seasons *Geophys. Res. Lett.* **42** 4394–401

Yuan X, Wang L and Wood E F 2018a Anthropogenic intensification of Southern African flash droughts as exemplified by the 2015/16 season *Bull. Am. Meteorol. Soc.* **99** S86–S90

Yuan X, Wang L, Wu P, Ji P, Sheffield J and Zhang M 2019 Anthropogenic shift towards higher risk of flash drought over China *Nat. Commun.* **10** 4661

Zeng J, Yuan X, Ji P and Shi C 2021 Effects of meteorological forcings and land surface model on soil moisture simulation over China *J. Hydrol.* **603** 126978

Zeng Z *et al* 2017 Climate mitigation from vegetation biophysical feedbacks during the past three decades *Nat. Clim. Change* **7** 432–6

Zeng Z, Piao S, Li L Z X, Wang T, Ciais P, Lian X, Yang Y, Mao J, Shi X and Myneni R B 2018 Impact of Earth greening on the terrestrial water cycle *J. Clim.* **31** 2633–50

Zhang M and Yuan X 2020 Rapid reduction in ecosystem productivity caused by flash drought based on decade-long FLUXNET observations *Hydrol. Earth Syst. Sci.* **24** 5579–93

Zhang X, Zhang L, Zhao J, Rustomji P and Hairsine P 2008 Responses of streamflow to changes in climate and land use/cover in the Loess Plateau, China *Water Resour. Res.* **45** 1–12

Zhang Y *et al* 2016 Multi-decadal trends in global terrestrial evapotranspiration and its components *Sci. Rep.* **6** 19124

Zhang Y, You Q, Mao G, Chen C, Li X and Yu J 2021 Flash drought characteristics by different severities in humid subtropical basins: a case study in the Gan River Basin, China *J. Clim.* **34** 7337–57

Zhou S *et al* 2017 Response of water use efficiency to global environmental change based on output from terrestrial biosphere models *Glob. Biogeochem. Cycles* **31** 1639–55