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Climate warming outweighs vegetation greening in intensifying
flash droughts over ChinaMiao Zhang^{1,2} , Xing Yuan^{1,2,*} , Jason A Otkin³ 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 China² School of Hydrology and Water Resources, Nanjing University of Information Science and Technology, Nanjing 210044, People's Republic of China³ Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin-Madison, Madison, WI 53706, United States of America

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E-mail: xyuan@nuist.edu.cn**Keywords:** flash drought, global warming, land cover change, trend, attributionSupplementary 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 CO₂ 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 CO₂ concentrations reduce stomatal conductance, which acts to decelerate the increasing drought frequency trend by 18%, whereas the physiological effects of rising CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 scales (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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ concentration at 1961 (CO₂_min) or 2016 (CO₂_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 CO₂ 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 CO₂ concentration (CO₂_min/CO₂_max) to distinguish the influence of warming, vegetation greening, and the physiological effects of CO₂ 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:

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

where $\text{Temp}_{i,j}$ is the real daily temperature in year i and season j , and $\text{Temp}_{adj,i,j}$ 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 CO₂ concentrations are

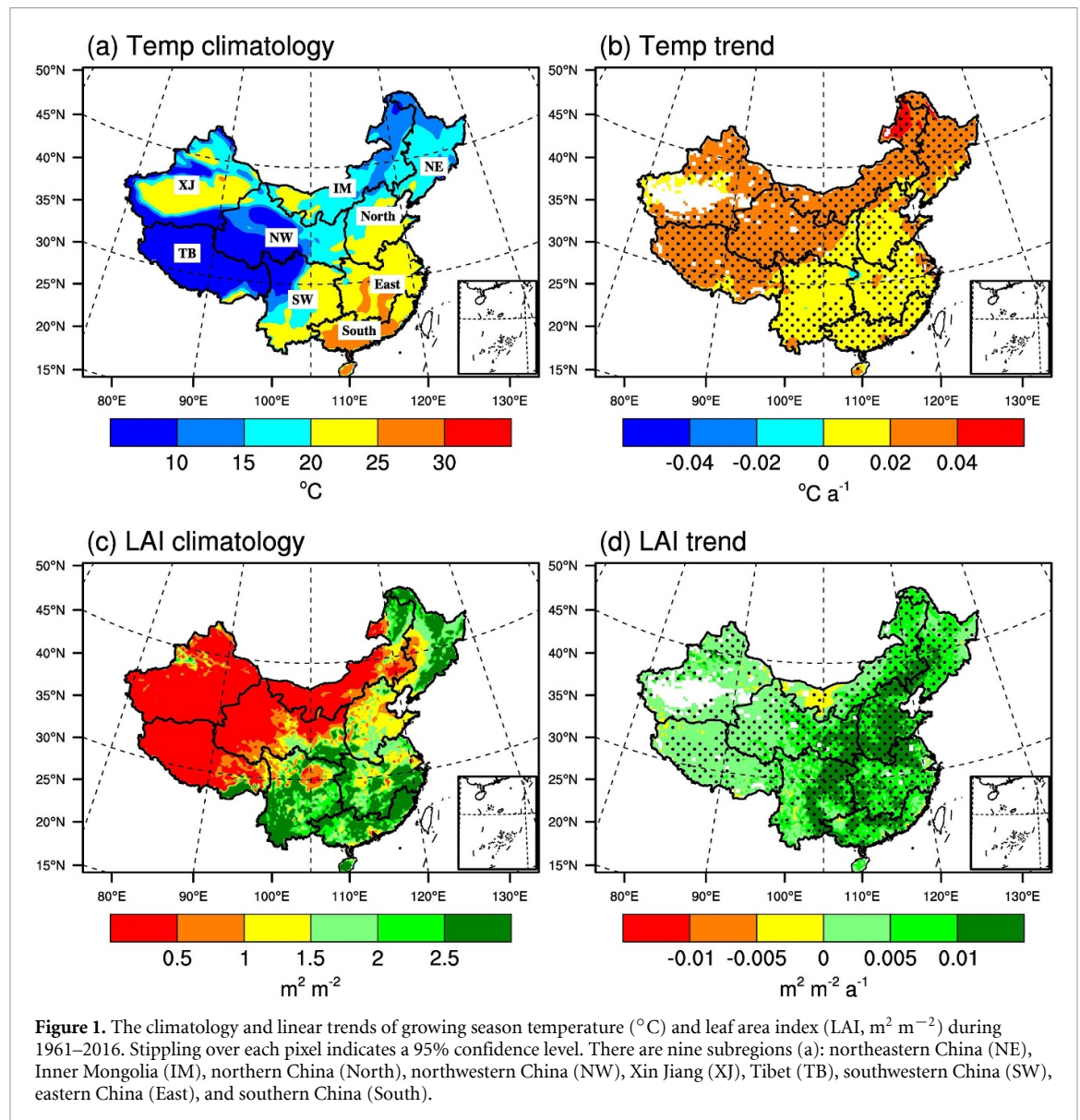
the same as those in CTL experiment with interannual variations and long-term trends. In a similar way, the annual time series of CO₂ concentrations were fixed in 1961 and 2016 in CO₂_min and CO₂_max, respectively, and meteorological forcings and LAI are the same as those in CTL.

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 CO₂ 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:

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

where $\text{trend}_{CTL-\text{exp } 1,\beta}$ and $\text{trend}_{CTL-\text{exp } 2,\beta}$ 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 $\text{trend}_{\alpha,\beta}$ is the contribution of the factor



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 $\text{trend}_{\text{CTL-exp1},\beta}$ and $\text{trend}_{\text{CTL-exp2},\beta}$ 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 ($>20^{\circ}\text{C}$) and low over Tibet and northwestern China ($<10^{\circ}\text{C}$; 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 $0.87 \text{ m}^2 \text{ m}^{-2}$ 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)).

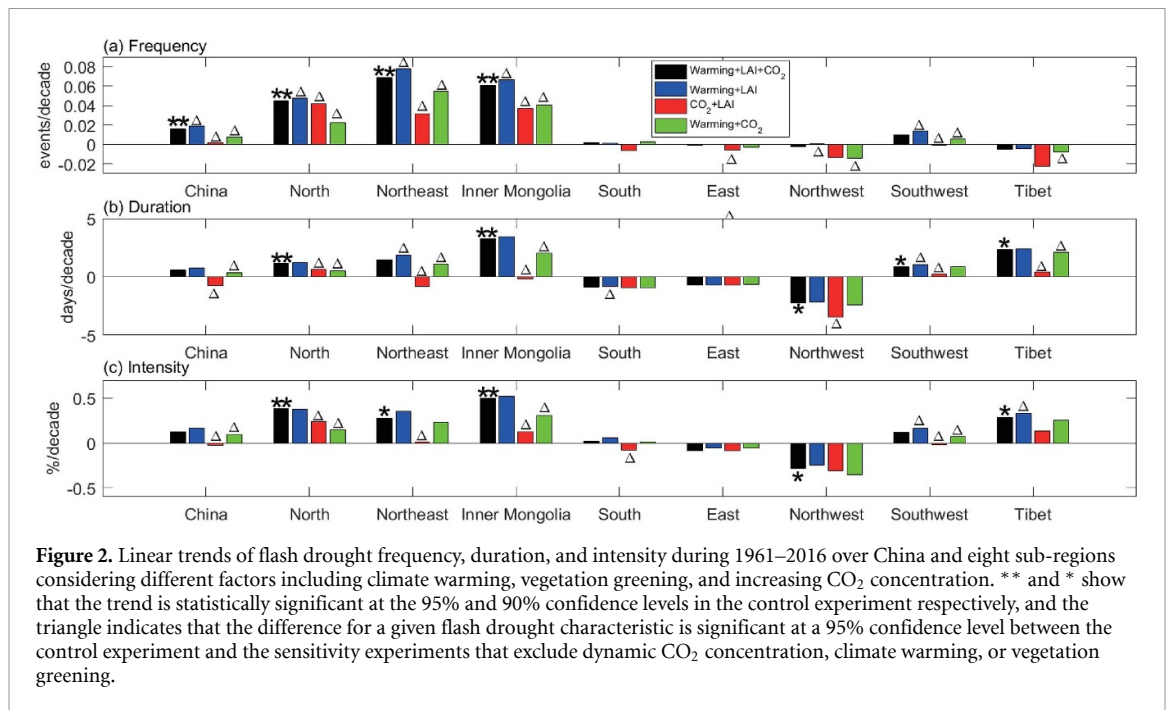
In the experiments of CO_2 _min and CO_2 _max, the influence of rising CO_2 concentration on flash droughts is ignored and the average mean of trends of flash drought characteristics in CO_2 _min and CO_2 _max is used here, which are only under the influence of climate warming and vegetation greening. 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 ($>0.003 \text{ m}^3 \text{ m}^{-3}$ 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



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 CO₂ 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 CO₂ concentration. The soil moisture generally decreases due to increasing LAI and climate warming, whereas the soil moisture increases as CO₂ 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 CO₂ 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 intensify 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 CO₂ concentration results in stomatal closure and decreases stomatal conductance, thus the ET change induced by high CO₂ concentration shows a decreasing trend (figure 3(f)), and the runoff is increased (figure 3(i)).

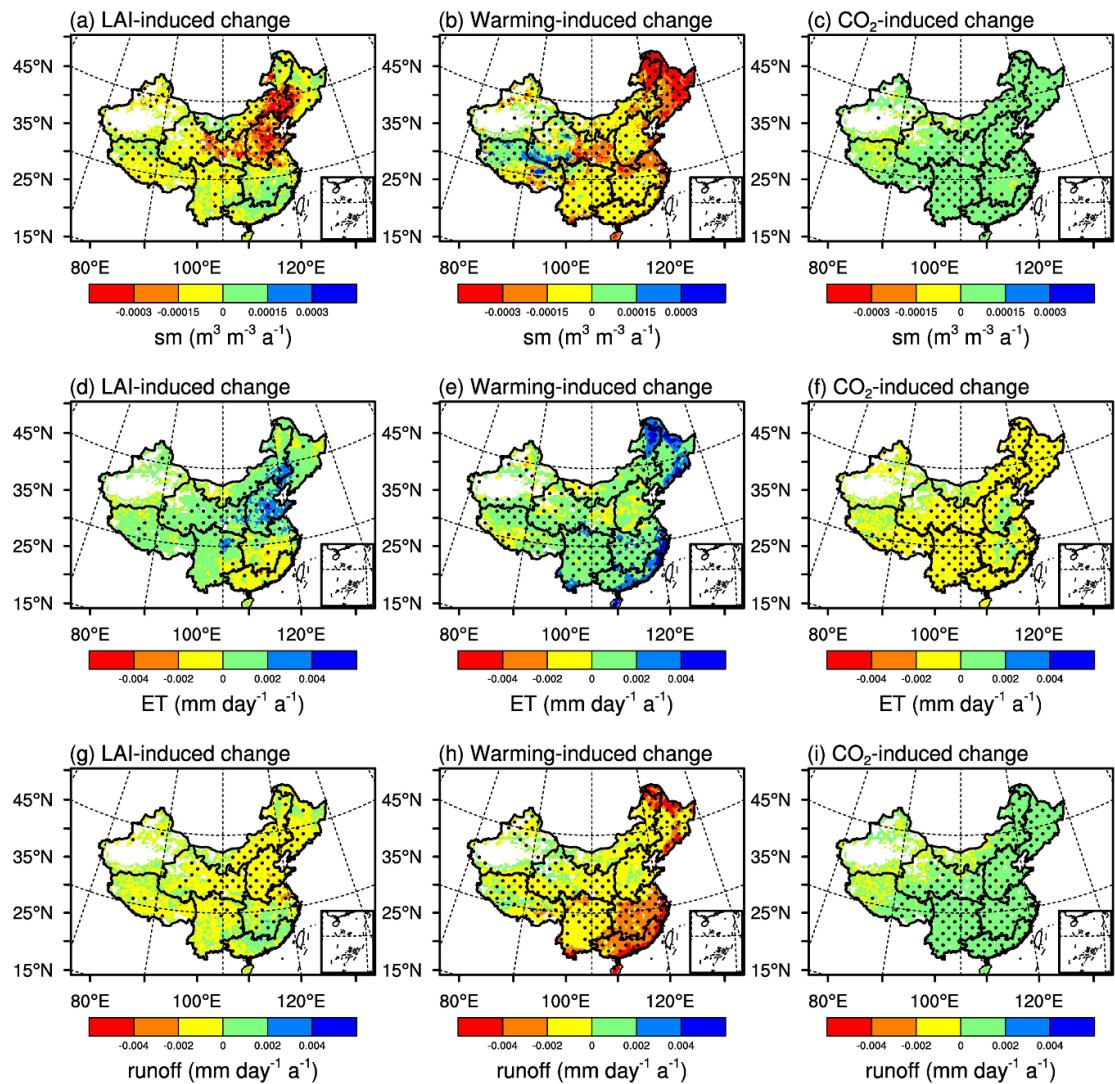


Figure 3. Linear trends of changes in soil moisture, evapotranspiration, and runoff induced by vegetation greening (a), (d) and (g), climate warming (b), (e), (h), and increasing CO₂ concentration (c), (f) and (i).

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 CO₂ 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 CO₂ on flash droughts are separated. Over all of China, warming, vegetation greening, and increasing CO₂ 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 CO₂ physiological effects are more consistent over China, that

is, higher CO₂ concentration results in wetter soils and larger runoff and decreases in ET. However, the compensatory effects of rising CO₂ 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 CO₂ 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 CO₂ 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/dtm7/>. 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.

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Conflict of interest

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

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