Anthropogenic Warming Has Increased the 2020 Extreme Hot and Dry Conditions over Southwest China

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Anthropogenic influence has increased the risk of the hot and reduced precipitation extremes similar to June 2020 over southwestern China with probability ratios (PR), relative to the preindustrial period, of 2.7 (5%–95% CI: 2.1–3.4) and 1.5 (5%–95% CI: 1.2–1.8), respectively.

Severe spring to early summer drought over Southwest China (SWC) in 2019 caught the public by surprise with its extreme intensity and damage (Ding and Gao 2020; Lu et al. 2021; Wang et al. 2021). Having still not fully recovered from this event, SWC then encountered one of its worst droughts on record in spring to early summer 2020 (the March–June mean ranks 13th and June ranks first in dryness since records began in 1961). Compared to the 2019 drought, the 2020 drought was episodic, developed rapidly from March to April due to the exceptionally high temperature and low precipitation, was slightly alleviated by sporadic precipitation during late April and May, and strengthened again to the lowest precipitation and highest temperature on record in June. This severe 2020 drought, especially in June, has raised questions about anthropogenic drought influences because of its large-scale damage to the local ecology, agriculture, and economy.

Usually a humid region, SWC has suffered more frequent and severe droughts in recent decades (Li et al. 2019; Yan et al. 2017; Ding and Gao 2020). According to previous research on SWC droughts, persistent abnormal sea surface temperature (SST) over the tropical Pacific and Indian Oceans (Ju and Chen 2003; Liu et al.

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2011; Cao et al. 2014; Wang et al. 2015a) changed atmospheric circulation including the intensification and westward shift of the western Pacific subtropical high (WPSH; Zou and Gao 2007; Zhang et al. 2013; Wang et al. 2015b), contributing greatly to a precipitation deficit over SWC. Additionally, the India-Myanmar trough, located in the Bay of Bengal, has a strong influence on SWC precipitation. Ding and Gao (2020) indicated that weakened water vapor transport due to the weakening India-Myanmar trough is the main cause of SWC drought. Recently, anthropogenic influence has also been found to increase extreme droughts in this region (Du et al. 2021; Lu et al. 2021; Wang et al. 2021). However, it is still unclear whether the 2020 extreme hot and dry event can be attributed to anthropogenic climate change. A case study is timely for developing appropriate strategies for mitigating SWC drought threats. Considering the severity of the impacts of the extreme event (Philip et al. 2020), we quantify the contribution of anthropogenic climate change to the extreme hot drought over SWC (20°–30°N, 97°–104°E; red box in Fig. 1a) in June 2020, and briefly discuss the cause of this extreme event from the perspective of anomalous circulations.

Dataset and methods.

Daily surface air temperature (T2M) and precipitation observations from 1961 to 2020 from 2,472 stations interpolated into 0.5° × 0.5° grid cells with the thin plate spline method (Shen et al. 2010) were obtained from the China Meteorological Administration (CMA) and converted into monthly means. To estimate data trends we used the Mann-Kendall non-parametric trend test. Here, temperature anomaly (Ta) and precipitation anomaly percentage (PAP) were calculated relative to 1981–2010 climatology, to quantify hot and dry intensity. As for the observations, return periods were calculated based on a normal distribution with a co-varying location parameter that used 4-yr smoothed global mean surface temperature (GMST) (Philip et al. 2020). Extreme hot (dry) events were defined as the highest (lowest) 15% of the regional mean Ta (PAP) in June (Wang et al. 2019). If both extremes occurred in the same year, it was considered as a hot drought event assuming independence of drought and heat (Diffenbaugh et al. 2015; Chen and Sun 2017; Wang et al. 2021). Concurrently, we calculated the joint return period by using Student's *t* copula fit to analyze the probability of simultaneous dry and hot (Demarta and McNeil 2005; Sun et al. 2019; see the online supplemental material).

To analyze circulation fields associated with the 2020 extreme hot drought, monthly eddy geopotential height (Z'; see the supplemental material) and wind datasets derived from NCEP–NCAR reanalysis (Kalnay et al. 1996) were also used.

Monthly T2M, precipitation and geopotential height simulations from the Coupled Model Intercomparison Project phase 6 (CMIP6; Eyring et al. 2016) model outputs including the historical all (ALL) and natural only (NAT) forcings since 1961, were used (see Table ES1 in the online supplemental information for the model list and detailed information). Kolmogorov–Smirnov tests were conducted to determine how well the simulated precipitation and temperature distributions matched the observed, which have weakness about low sensitivity in the case of a known distribution. Here, 52 simulations from 12 models were selected, which have been proven to match well with the observed distribution (see Fig. ES1). To quantify the contributions of anthropogenic influence to the extreme hot drought over SWC in June 2020, the corresponding probability ratio (PR; Fischer and Knutti 2015) was calculated, with the definition of PR = P_{ALL}/P_{NAT}. Here, P_{NAT} and P_{ALL} denote the probability of exceeding the observed 2020 extreme conditions in the NAT and ALL forcing simulations, respectively, based on the normal distribution for the entire time series. The 5%–95% confidence intervals (CIs) were estimated with 1000-member bootstrapped samples over 52 simulations (Efron and Tibshirani 1994).

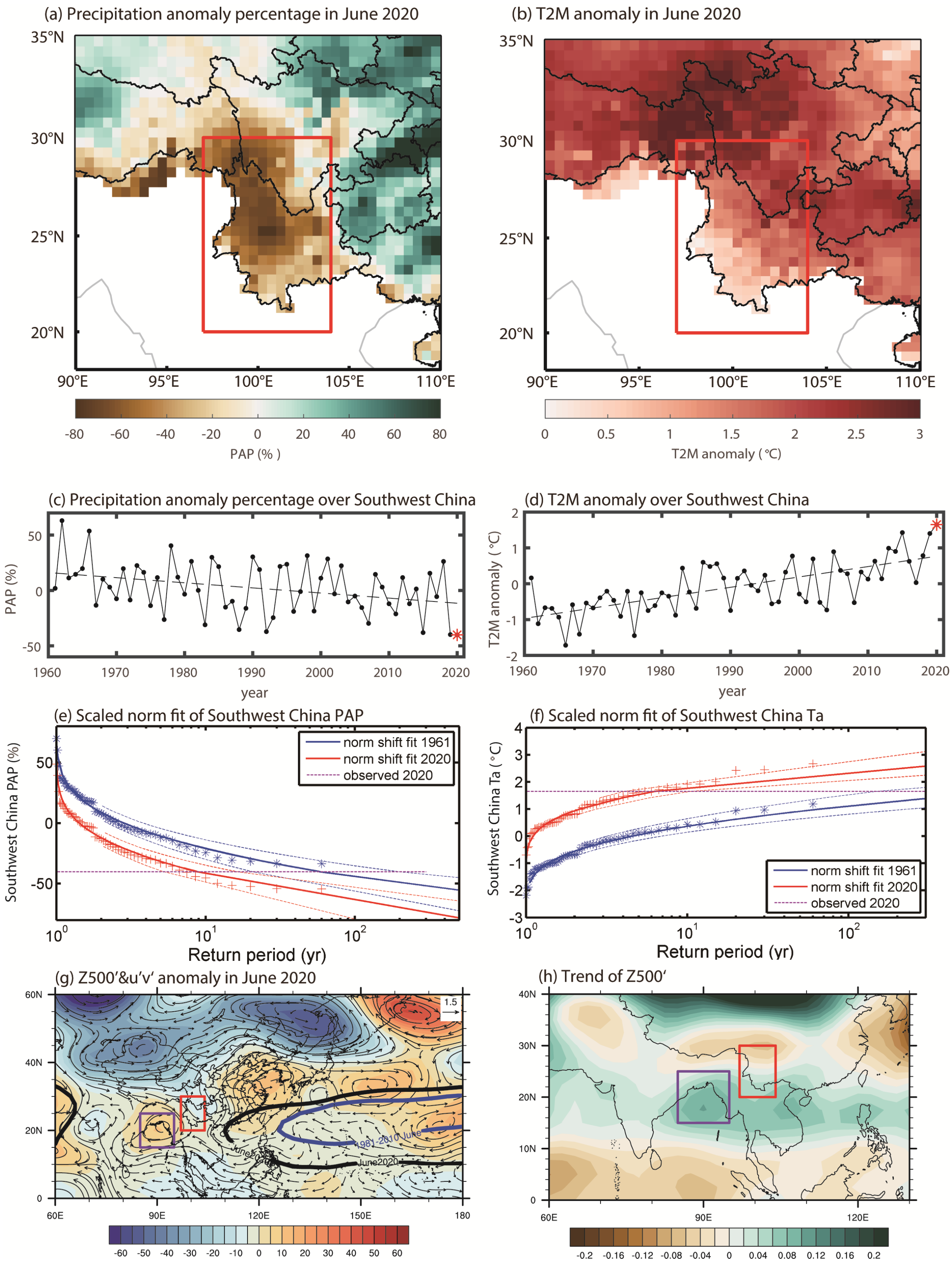

Fig. 1. (a) Precipitation anomaly percentage (PAP; unit: %) and (b) temperature anomaly (Ta; unit: °C) in June 2020 relative to 1981–2010 climatology based on CMA observation. Also shown are regional means of June (c) PAP and (d) Ta over southwest China (SWC) respectively, where the red markers represent the year 2020, and return periods for (e) PAP and (f) Ta over SWC in the 2020 climate (red lines with 95% CI) and the 1961 climate (blue lines with 95% CI). A normal distribution is used that shifts with the 4-yr smoothed global mean surface temperature. (g) Eddy 500-hPa geopotential height anomalies (Z500; unit: m; shading) and their corresponding winds anomalies ($u'v'$; vector; unit: m s^{-1}) in June 2020, superimposed with 588-dagpm contours (in black) and climatological June mean 588-dagpm contour (in blue) for 1981–2010. (h) Trend of Z500′ over the Bay of Bengal (purple box). The red box is the study region (20°–30°N, 97°–104°E).

Results.

The PAP spatial distribution (Fig. 1a) shows that SWC experienced an exceptionally drier June than normal, especially in northwest Yunnan province, which received only 20% of its climatological precipitation. The regional average precipitation in June 2020 was unprecedentedly low, about 40% less than the 1981–2010 climatology (Fig. 1c). The June precipitation over SWC experienced a significant drying trend over 1961–2020 with the rate of −0.44% decade^{-1} (95% confidence level using a Mann-Kendall test). A normal fit of the observed PAP denotes that the 2020 extreme precipitation deficit was a 1-in-9-yr event in the current 2020 climate and a 1-in-58-yr event in the 1961 climate (Fig. 1e). Concurrently, the entire SWC was dominated by exceptionally high temperature (Fig. 1b), which was the hottest June since records began in 1961, with anomalies exceeding 2°C in most regions. Notably, the driest regions were not the hottest, which is possibly due to heat and drought interactions varying with population density, urbanization, and other factors (Trenberth and Shea 2005; Yu and Zhai 2020). For the regional mean time series (Fig. 1d), the SWC had the hottest recorded June in 2020 at 1.64°C higher than normal. Such an extremely hot June occurs only once in about 1000 years (in past 1961 climate) while its return period shortened to 1 in 58 years in the 2020 climate (Fig. 1f). As for concurrence of hot and drought events, the joint return period through a Student's *t* copula fit (Demarta and McNeil 2005; Sun et al. 2019) was performed and showed that concurrent hot and dry in June 2020 was a 1-in-244-yr event.

It is known that the drought is always associated with persistent or persistently recurring circulations that produce little or no precipitation (Lü et al. 2012; Ding and Gao 2020). In June 2020, the low to middle latitudes were dominated by high pressure anomalies, and thus the WPSH strengthened and shifted westward significantly relative to 1981–2010 climatology (Fig. 1g). The westward WPSH extension made the subtropical high connect with the Iranian high (see Fig. ES2), which prevented water vapor transport to SWC (Ding and Gao 2020; Wang et al. 2021). Concurrently, there was an anticyclonic (cyclonic) anomaly around the Bay of Bengal (northwestern China) with an anomalous northwesterly between them, which may have weakened the India-Myanmar trough, and inhibited water vapor transport from the Bay of Bengal (BOB) to SWC (Ding and Gao 2020), thereby impacting the extreme June 2020 drought. A record strong Indian Ocean dipole (IOD) in late 2019 is also a possible contributor to sustained warming in the tropical Indian Ocean during spring to early summer 2020, thereby exciting an anomalous anticyclone over the BOB (Zhou et al. 2021). An eddy geopotential height trend (Fig. 1h) shows a similar distribution with anomalous high pressure around the BOB and anomalous low pressure to its north, which probably caused decreasing precipitation in recent decades.

Figure 2 shows the likelihood changes of extreme hot and dry over SWC by comparing their probability in the CMIP6 simulations with and without anthropogenic forcing. There exists a leftward shift of the probability density functions (PDFs) for rainfall and a rightward shift for temperature due to anthropogenic climate change, with PR values 1.5 (5%–95% CI: 1.2–1.8) and 2.7 (5%–95% CI: 2.1–3.4), respectively. When we varied the spatial domain [as in Lu et al. (2021)], the corresponding probability ratios and their 5%–95% confidence intervals were still greater than 1. Furthermore, the concurrence of extreme heat and drought events was investigated, and results show that the frequency of concurrent hot and dry extremes in June significantly increased since the middle 1990s under the influence of anthropogenic climate change (Fig. 2c). We also used the joint probability distribution to estimate the results, and obtained a similar conclusion (Fig. 2d). In the last 10 years, for example, these concurrent hot and dry extremes have been about twice as likely when compared with NAT simulations, which is probably due to increasing actual evapotranspiration and decreasing soil moisture from climate warming (Zhang et al. 2020). When we changed the region to the that used by Lu et al. (2021), it showed the same results (see the online supplemental material).

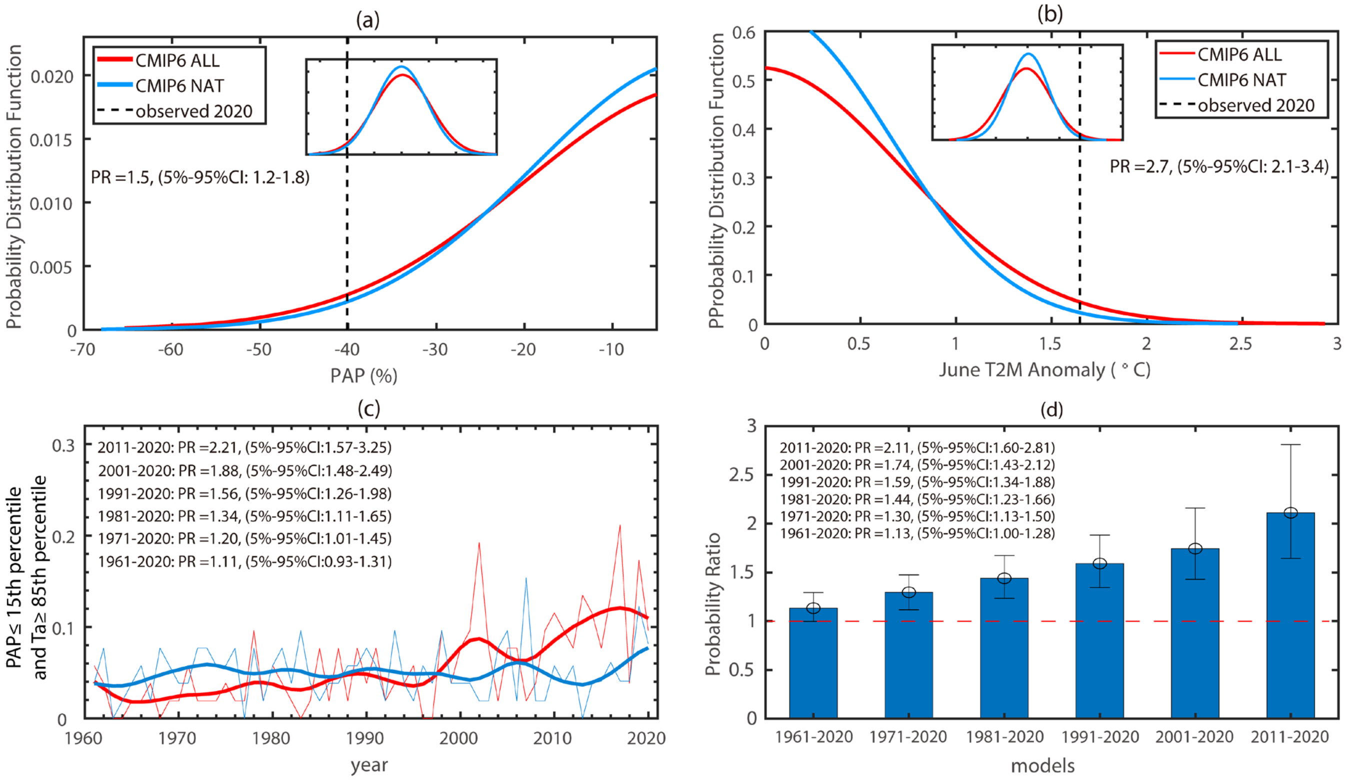

Fig. 2. Probability density functions (PDFs; curve) of (a) precipitation and (b) temperature in June over SWC from CMIP6 simulations under historical (ALL; in red) and hist-nat (NAT; in blue) forcings during 1961–2020. (c) The probability of concurrent extremely low precipitation and high temperature. The bold curves show the 11-yr running mean of the annual time series. The *p* values indicate the significance level of the difference between the ALL and NAT forcing for the most recent 10, 20, 30, 40, and 60 years. (d) As in (c), but calculated using Student's *t* copula fit. The insets in (a) and (b) show the full PDF distribution.

Conclusions.

In 2020, repeated droughts occurred in SWC, reaching their peak in June, with the lowest precipitation and unprecedented high temperature since modern records began in 1961, thereby causing great economic and social losses to the region. Associated circulation analysis suggested that WPSH enhancement and an anticyclone anomaly over the BOB largely contributed to this extreme hot drought in SWC, possibly by reducing water vapor transportation to Yunnan and weakening local upward motion over SWC. A similar circulation pattern was also found in last year's drought over SWC (Ding and Gao 2020; Wang et al. 2021). Attribution analysis based on CMIP6 ALL and NAT simulations indicated that anthropogenic climate change has increased the likelihood of extremely low precipitation in SWC, such as occurred in 2020, by about 50% (5%–95% CI: 20%–80%) and the likelihood of extremely high temperature by about 170% (5%–95% CI: 110%–240%). Moreover, it should be noted that the PR of such concurrent hot and dry extremes has increased to 1.6 times in the recent 30-yr period due to anthropogenic climate change. Furthermore, anthropogenic warming has generally accelerated hydrological processes, resulting in hot and dry events becoming more frequent (Naumann et al. 2018; Mukherjee et al. 2018). Contributions of direct anthropogenic, or indirect influence on the circulation to dry and hot events deserve further study.

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