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Attribution of the Extreme 2022 Summer Drought along the Yangtze River Valley in China Based on Detection and Attribution System of Chinese Academy of Sciences

Lixia Zhang,^{a,b,c} Tianjun Zhou,^a Xing Zhang,^a Wenxia Zhang,^a Lijuan Li,^a and Laurent Li^d

1. Introduction

The Yangtze River, the longest river in Asia, feeds about one-third of the population of China. In the summer 2022, the Yangtze River valley (YRV) was hit by an extreme drought unprecedented since 1961 with low precipitation (Pr) and high surface air temperature (Tas) (Figs. 1a,b). The area-averaged Pr over YRV (26°–34°N, 90°–122°E) in 2022 was –24.8% less than the baseline of 1961–2020, and Tas was 2.0°C higher, both breaking the record since 1961 (Fig. 1c).

The number of drought days, the area affected by drought in a single day, and the proportion of stations affected by exceptional drought all reached record high (National Climate Centre 2022). Persistent precipitation deficit, heatwaves, and high consumption of drinking water and agricultural water caused dramatic river inflow shrinkage and unprecedented low water levels, leading to severe power outages and ecosystem damages along the YRV, and unseasonal wildfires in Sichuan Province and Chongqing (Ma et al. 2022; Hao et al. 2023).

Several factors were responsible for this drought, including large-scale atmospheric anomalies forced by La Niña (Tang et al. 2023; He et al. 2023), intraseasonal oscillation from mid-June to late August (Liu et al. 2023; D. Zhang et al. 2023), land–air interactions (Jiang et al. 2023), and anthropogenic global warming (Qian et al. 2022). Here, our study aims to answer how human-induced climate change alters the intensity and likelihood of the unprecedented summer drought in 2022 along the YRV by investigating Pr, Tas, and the prevalent circulation conditions from two large-ensemble simulations with and without human influence.

AFFILIATIONS: ^a State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China; ^b China Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, China; ^c Key Laboratory of Cities' Mitigation and Adaptation to Climate Change in Shanghai, China Meteorological Administration, Shanghai, China; ^d Laboratoire de Météorologie Dynamique, CNRS, Sorbonne Université, Paris, France

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Corresponding author: Lixia Zhang, lixianghang@mail.iap.ac.cn

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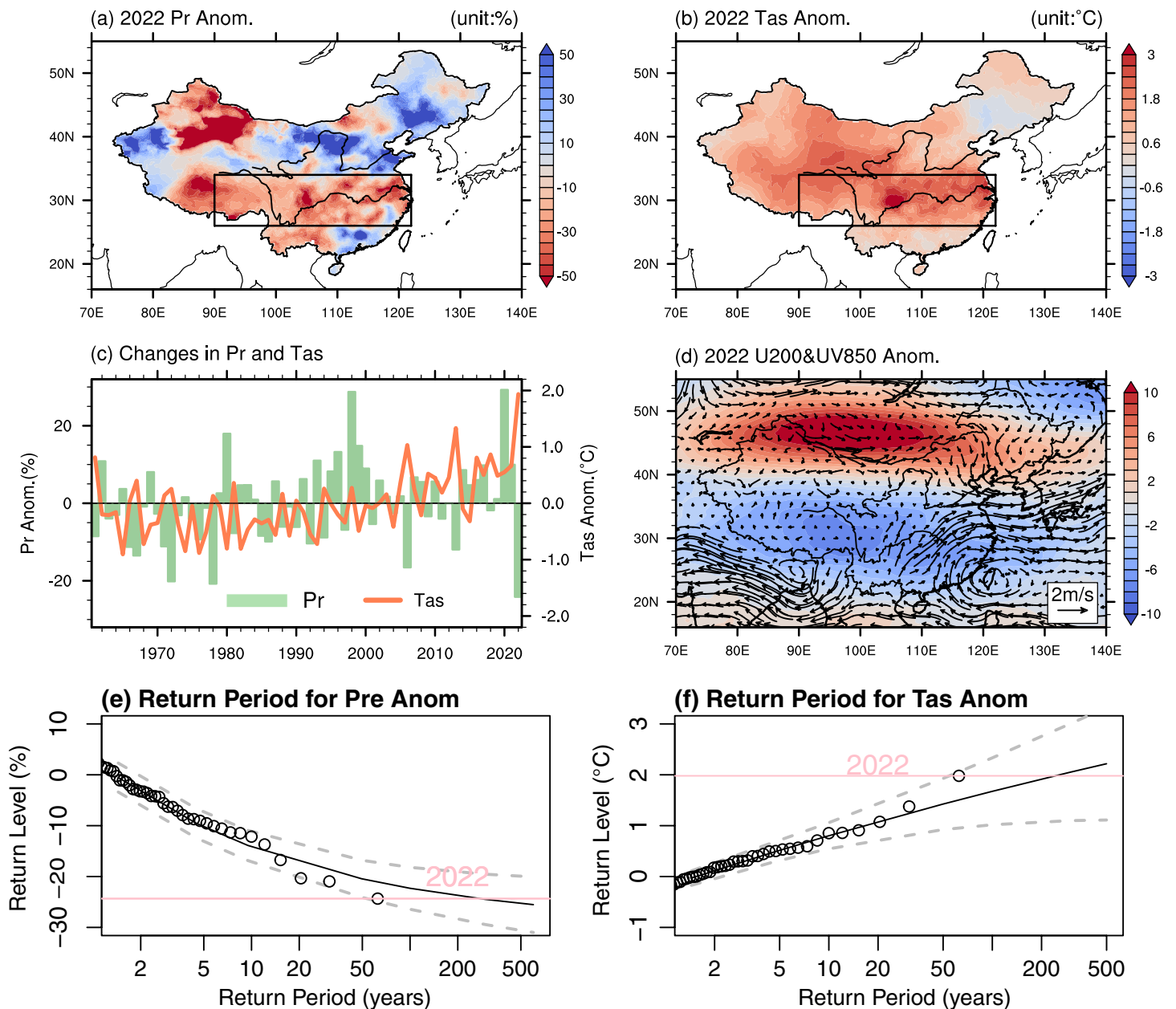


FIG. 1. The observed anomalies in summer (June–August) (a) precipitation (Pr; %) and (b) surface air temperature (Tas; °C) in 2022 relative to 1961–2020. (c) Area-averaged Pr (bar; left y axis) and Tas (line; right y axis) anomalies over the YRV [black box in (a) and (b)] from 1961 to 2022. (d) Anomalies in 850-hPa winds (vector; m s^{-1}) and zonal wind at 200 hPa (shading; m s^{-1}) in the summer 2022 relative to 1961–2020. (e),(f) Return level (black lines) plots and 95% CIs (gray dotted lines) for summer mean Pr and Tas anomalies averaged over the YRV, where the pink line shows the anomalous level in 2022.

2. Data and methods

We conducted two experiments for the actual climate with all external forcing (“ALL”) and for a hypothetical natural climate without human influence (“NAT”) using Grid-point Atmospheric Model of the IAP LASG, version 3 (GAMIL3.0) (Li et al. 2020a,b). It is named as Detection and Attribution System of the Chinese Academy of Sciences (CAS-DASys; D. Zhang et al. 2023). The experiment design followed the International CLIVAR C20C+ Detection and Attribution project (Stone et al. 2019) but with external forcings updated to CMIP6. In ALL, greenhouse gases, anthropogenic aerosols, and land use were the same as the historical forcings of CMIP6 up to 2014 and followed the shared socioeconomic pathway (SSP) 2-4.5 scenario afterward (Eyring et al. 2016). Observed sea surface temperature (SST) and sea ice concentration (SIC) were from HadISST1 (Rayner et al. 2003). In NAT, the greenhouse gases, anthropogenic aerosols, and land use were prescribed at the level of 1860, and SST and SIC

were derived by subtracting the anthropogenic forced changes from HadISST1. The anthropogenic forced SST and SIC changes were estimated as the difference between ALL and NAT simulations of CMIP6 multimodel mean (Stone and Pall 2021), which was obtained by first conducting multirealization mean for each model and then the unweighted average across all models (Table S1 in the online supplemental material).

We conducted 50 members' historical simulations for 1961–2020 and 400 members for summer (June–August) 2022 by perturbing initial conditions. The observation and circulation datasets are monthly Pr and Tas from CN05.1 (Wu and Gao 2013) and ERA5 reanalysis for 1961–2022 (Hersbach et al. 2020), respectively. The Pr and Tas anomalies relative to 1961–2020 were utilized to measure the drought intensity, representing the water supply and evaporative demand, respectively.

To estimate the contribution of atmospheric circulation to the 2022 event, we used a flow analog method to examine the 2022 drought under similar circulation conditions with and without anthropogenic forcing (Jézéquel et al. 2018). The circulation proxies are the anomalous summer 850-hPa winds and 200-hPa zonal wind over the region (15°–55°N, 70°–140°E). For each summer month of 2022, we search the 20 analog months with the most similar field among the summer months of NAT and ALL using the Euclidean distance, respectively. Before calculating the Euclidean distance, each wind anomaly was first normalized by its standard deviation during 1961–2020 to ensure homogeneity among variables. We then reconstructed Pr and Tas anomalies under conditions on the selected circulations as follows: (i) randomly picked one of the 20 best analog months in NAT and ALL for each summer month, respectively; (ii) calculated the average of the Pr and Tas anomalies; (iii) repeated the above two steps 5000 times and finally got ranges of Pr and Tas anomalies conditional on the observed anomalous circulations of 2022 summer.

The exceedance probability for 2022-like extreme events was estimated from the generalized extreme value (GEV) distribution. We estimated the 95% confidence intervals (CI) with a 1000-member bootstrap with replacement.

3. Results

a. The 2022 summer drought in historical context. This unprecedented summer drought was caused by a joint role of enhanced northwestern Pacific subtropical high (NWPSH) at the low level and strengthened South Asian high (SAH) at the upper level (Fig. 1d; D. Zhang et al. 2023; Zhou et al. 2023). The anticyclone anomalies at 850 hPa were westward expanded to the eastern flank of the Tibetan Plateau, and the SAH was strengthened with stronger westerlies around 40°–50°N and easterlies to the south. The return period for the anomalies in Pr and Tas in 2022 is estimated to be approximately once in 270 years (95% CI: 40 year to never happen) and 240 years (30 year to never happen), respectively (Figs. 1e,f).

b. Contribution of human-induced climate change. The ranges of observed anomalies of Pr and Tas align well with those from the large-ensemble simulations of GAMIL3.0 (Fig. S1). The Kolmogorov–Smirnov test indicated that, at a 5% significance level, the empirical distribution function of Pr and Tas anomalies from observation and simulation cannot be distinguished. Simulated parameters of the GEV density functions for Pr and Tas anomalies fall within the observed ranges (Table S2). This demonstrates a reasonable simulation of the variation in YRV Pr and Tas anomalies during 1961–2020 by GAMIL3.0.

We presented the role of human influences on the 2022 YRV summer drought in Fig. 2. Our simulations clearly demonstrated that drought can arise from natural variability, but anthropogenic forcing amplifies its intensity and increases its probability. There is an intensified drought along the YRV during the summer of 2022 in ALL compared to NAT (Figs. 2a,b, Fig. S2). The YRV is drier by -0.9% (from -15.7% to 17.6%) and warmer by 0.5°C

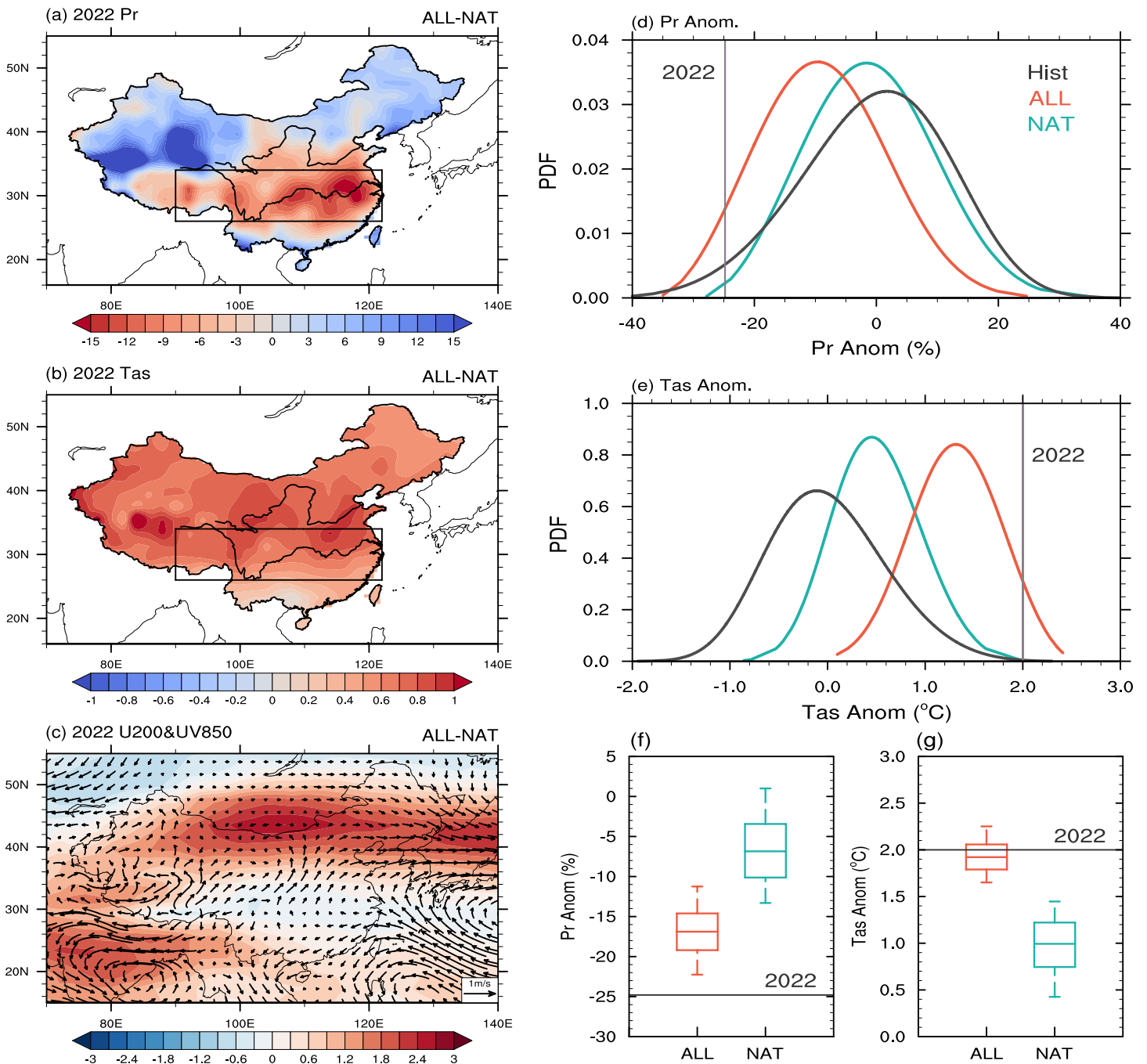


FIG. 2. The difference in 2022 summer (a) Pr (%), (b) Tas (°C), and (c) circulations between the 400-member mean of "ALL" and "NAT." Shading and vectors in (c) are for the anomalies of zonal wind at 200 hPa and winds at 850 hPa (m s^{-1}), respectively. GEV distributions of the summer mean (d) Pr (%) and (e) Tas (°C) averaged over the YRV from historical ("Hist," gray), Nat (green), and ALL (blue) simulations. The vertical gray lines in (d) and (e) denote the thresholds observed in 2022 summer. Distributions of the reconstructed (f) Pr and (g) Tas anomalies using the flow analog method based on simulations for 2022 summer with (red) and without (green) anthropogenic forcings. The three lines of the boxplots indicate the 5th percentile, median, and 95th percentile from bottom to top, respectively, from 5000 subsamples. The horizontal lines in (f) and (g) represent the observed intensity of the event.

(from -0.2° to 1.1°C) under natural forcing relative to the climate mean. Anthropogenic forcing contributed to an additional 7.9% (7.8%–24.1%) reduction in precipitation and 0.8°C (0.1° – 1.5°C) warmer Tas compared to natural forcing (Figs. 2d,e). Concerning the likelihood of the 2022 event, it rises from 0.07% (0.05%–4.5%) in NAT to 4.8% (3.3%–6.1%) in ALL for Pr, and from 0.005% (0.002%–0.07%) to 6.3% (4.9%–9.8%) for Tas. Human forcing has increased the likelihood of drought such as in 2022 by 65 (1–90) times for Pr and 1300 (90–3000) times for Tas, respectively, measured by risk ratio (Stott et al. 2004).

We further examined the circulation anomalies associated with this drought event (Figs. 2c,f and Figs. S2c,f). The intensified western North Pacific subtropical high (WNPSH) and SAH in 2022 summer were captured by ALL and NAT (Figs. S2c,f), aligning with findings from Tang et al. (2023) by forcing Community Atmospheric Model, version 6.0, with observed SST. They showed that the triple La Niña induced the second-highest SST gradient in the equatorial western Pacific, suppressing the western Pacific convection and extended the WNPSH westward. Anomalous diabatic heating associated with the unprecedented Pakistan rainfall, partly due to La Niña, reinforced the downstream Rossby wave train and intensified the upper-level SAH.

Our simulations show that WNPSH and SAH in 2022 were intensified when human influence was included (Fig. 2c). The contribution of atmospheric circulation, derived from the flow analog method, has resulted in a 17% (14%–19%) reduction in Pr and a 1.9°C (1.7°–2.1°C) increase in Tas in ALL, highlighting the substantial role of circulation. In comparison, atmospheric circulation in NAT leads to only a 7% (3%–13%) reduction in Pr and 1.0°C (0.7°–1.2°C) increase in Tas (Figs. 2g,f). This suggests that the circulation contribution has nearly doubled under anthropogenic forcings. The attribution in this study indicates that human influences tend to intensify the WNPSH and SAH, thereby increasing the intensity and the likelihood of the extreme 2022 drought along the YRV.

4. Conclusions

The Yangtze River valley was hit by drought in 2022 summer unprecedented since 1961, with record low precipitation and high temperature. It was caused by a combination of enhanced NWPSH and SAH. We used GAMIL3.0 to conduct two large-ensemble simulations for the climate with all external forcing and for a hypothetical natural climate without human influence, to assess the role of human influence on the intensity and probability of 2022-like extreme drought along the YRV.

The analysis indicated that human influences tend to amplify the summer WNPSH and SAH in 2022, consequently increasing the intensity and likelihood of extreme drought. Human forcing contributed to a 7.9% (7.8%–24.1%) reduction in precipitation and 0.8°C (0.1°–1.5°C) warming in Tas along the YRV and increased the likelihood of this event from 0.07% (0.05%–4.5%) to 4.8% (3.3%–6.1%) for Pr deficit, and from 0.005% (0.002%–0.07%) to 6.3% (4.9%–9.8%) for Tas, respectively. Thus, the risk has increased by 65 (1–90) times for Pr and 1300 (90–3000) times for Tas in 2022 due to human influence. The higher risk of extreme drought along the YRV due to human influence poses serious challenges for decision-makers and the society in the energy–food–water–ecology nexus to better adapt to increasing drought in the future.

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