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## **Anthropogenic influence on the record-breaking compound hot and dry event in summer 2022 in the Yangtze River Basin in China**

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## Abstract

CMIP6 simulations suggest that the probability of the compound hot and dry event occurring in summer 2022 in the Yangtze River Basin in China is enhanced by anthropogenic effect by 7 times.

## Introduction

In summer 2022, the Yangtze River basin in China experienced an exceptional hot event. Its intensity reached the strongest level since complete meteorological observations began in 1961 (Figure 1b, e). Due to reduced precipitation and prolonged high temperature, the Yangtze River basin experienced an unusual dry summer (Figure 1 a, e), the dry conditions peaked around mid to late August. The severity of this compound event, which occurred simultaneously with heat and dryness, also broke historical records (Figure 1 e). This compound event resulted in rivers and reservoirs drying up, forest fires, and consecutive electricity loads exceeding historical extremes, causing damages on ecosystems with severe impacts on the regional socio-economics ([https://www.mem.gov.cn/xw/yjglbgzdt/202209/t20220917\\_422674.shtml](https://www.mem.gov.cn/xw/yjglbgzdt/202209/t20220917_422674.shtml)). The objective of this study is to investigate the impact of anthropogenic and natural factors on events similar to the case of 2022 in the Yangtze River basin.

## Data and Method

The observation data used in this study consists of monthly surface air temperature and precipitation with a resolution of  $0.5^{\circ} \times 0.5^{\circ}$  from 1961 to 2022. The data was retrieved from over 2000 quality-controlled weather stations in China (Wu and Gao, 2013), covering the Yangtze River basin (about  $105^{\circ}$ — $123^{\circ}$ E and  $28^{\circ}$ — $35^{\circ}$ N, black box in Figure 1a). We use the geopotential height anomalies at 500 hPa relative to 1991-2020 climatology from the NCEP-NCAR reanalysis to describe the circulation background of this event.

We also use data from six CMIP6 models run under both natural and anthropogenic forcings (ALL) and natural-only forcing (NAT), respectively, during 1961 to 2020 (Eyring et al. 2016). As the 2015-2020 segments of NAT simulations used natural forcing from the Shared Socioeconomic Pathway 2-4.5 (SSP2-4.5) scenario, the historical ALL simulations, normally ended in 2014, were simply completed to 2020 with their corresponding SSP2-4.5 scenario runs. Our practice here is identical to Hu et al. (2023). We interpolated monthly precipitation and surface air temperature from different models onto the grid of observation dataset using bilinear interpolation. The basic information of models used is listed in Table S1.

We use the Standardized Precipitation Index (SPI) to identify conditions of dryness (Vicente-Serrano and Lopez-Moreno, 2005). Similarly for hot event, the Standardized Temperature Index (STI) is adopted to reflect the conditions of heat (Hao et al., 2022). SPI and STI at 3-month scale are firstly calculated at each grid box and then regionally averaged (with grid area as weight) across the geographic domain for each member of the models. The seasonal mean from June, July and August is used to represent summer for both dry (by SPI) and hot (by STI) conditions. We used the Standardized Dry and Hot Index (SDHI) to represent the severity of compound hot and dry events (CHDEs)

(Hao et al., 2019). The joint probability  $p$  of CHDE can be expressed as:

$$p = P(X_1 \leq x_1 \cap X_2 \geq x_2) = F_1(x_1) - C(F_1(x_1), F_2(x_2)),$$

where  $F_1$  and  $F_2$  are the cumulative distribution function (CDF) for SPI and STI, respectively. The parametric-based normal distribution was employed to estimate the probability.  $C$  is the copula function (Nelsen, 2007), widely used in constructing the joint probability of multivariate variables. The best-fitting copula function is determined through the Akaike Information Criterion (AIC), favoring the one with smallest AIC value. The copula parameters are estimated using the maximum likelihood function, which is implemented in the R package VineCopula.  $p$  was then converted into a uniform distribution through fitting a distribution  $F$ , which was subsequently standardized to severe as an indicator for assessing the severity of CDHEs. The SDHI can be expressed as:

$$SDHI = \Phi^{-1}[F(p)].$$

Lower values indicate severe conditions.

Since we are dealing with yearly data, the return period of SPI and STI are simply  $\frac{1}{F_1(x_1)}$  and  $\frac{1}{1-F_2(x_2)}$ . The joint return period of non-exceedance threshold  $x_1$  for SPI ( $X_1$ ) and exceedance threshold  $x_2$  for STI ( $X_2$ ) can be expressed as follows:

$$T_{SPI,STI}^{AND} \frac{1}{P(X_1 \leq x_1 \cap X_2 \geq x_2)} = \frac{1}{F_1(x_1) - C(F_1(x_1), F_2(x_2))}$$

In this work, we are also interested in the anthropogenic influence on the likelihood of hot event occurring while a configuration of dryness ( $X_1 = x_1$ ) is fixed. This can be derived from the conditional probability density distribution:  $f(x_2|x_1) = c(F_1(x_1), F_2(x_2)) \cdot f_2(x_2)$ , where  $c$  is the copula probability density function (PDF) and  $f_2(x_2)$  is the PDF of STI. Once the conditional marginal PDF is constructed, the probability of STI exceeding a specific threshold can be calculated (Chiang et al., 2021).

The fraction of attributable risk ( $FAR = 1 - P_{NAT}/P_{ALL}$ ) is used to estimate the effect of anthropogenic influence on the occurrence probability of the 2022 event (Fischer and Knutti, 2015; Stott et al., 2016).  $P_{NAT}$  and  $P_{ALL}$  represent the probability of event under natural forcing and historical forcing, respectively. FAR can be interpreted as the fraction of the likelihood of an event that is attributable to the anthropogenic forcing. A bootstrap resampling was performed 1000 times to estimate the 90% confidence interval (CI) of FAR as in Christidis et al. (2013).

## Results

The majority of the study domain experienced extreme hot and dry conditions in 2022 (Figure 1a, b). The atmospheric circulation provided favorable background for these conditions. The Western Pacific Subtropical High (WPSH) was anomalously

westward shifted in June, July, and August (Figure S1). The entire basin was controlled by strong positive anomalies of geopotential height at 500 hPa (Figure 1c), corresponding to the peak of dry conditions in August. Such an anomalous circulation pattern prevented cold air in the north from moving southward. Simultaneously, in the region controlled by anomalous high-pressure, prevailing descending air inhibits precipitation and enhances warming through subsidence.

The average STI and SPI over the domain show significant correlation ( $r=-0.28$ ,  $p<0.05$ ), resulting from the influences of land-atmosphere interaction and the circulation anomalies. The main variability of SPI is at interannual. For STI, however, there is a clear decadal variability, characterized by decreasing trends before the 1990s and increasing trends afterwards. Domain-averaged STI of 2022 reaches to 1.88, breaking the observation record since 1961 (Figure 1d, e). The PDF deduced from historical observations indicates that the probability of such a hot event is nearly 0.007 (Figure 1d), corresponding to a return period of 150 years, with a 90% confidence interval of 59-721 years. Domain-averaged SPI of 2022 is -0.6 (Figure 1d, e), indicating a severe meteorological drought with the probability of 0.1. Such a dry event is a 1-in-10yr event (90% confidence interval: 1 in 7-17 yr). In terms of compound event combining both heat and dryness, a decrease of SHDI indicating an increase in severity of compound event was observed since 1990s, and the severity of 2022 compound event also largely broke the historical record (Figure 1e). The best Copula fit suggests that the return period of the 2022 hot and dry event is 753 years (533-1151 years for the 90% confidence interval; Figure 1f). It is to be noted that the longer return period of the compound event, relative to the single event, may be related to the heat-dryness negative correlation (Hao et al., 2022).

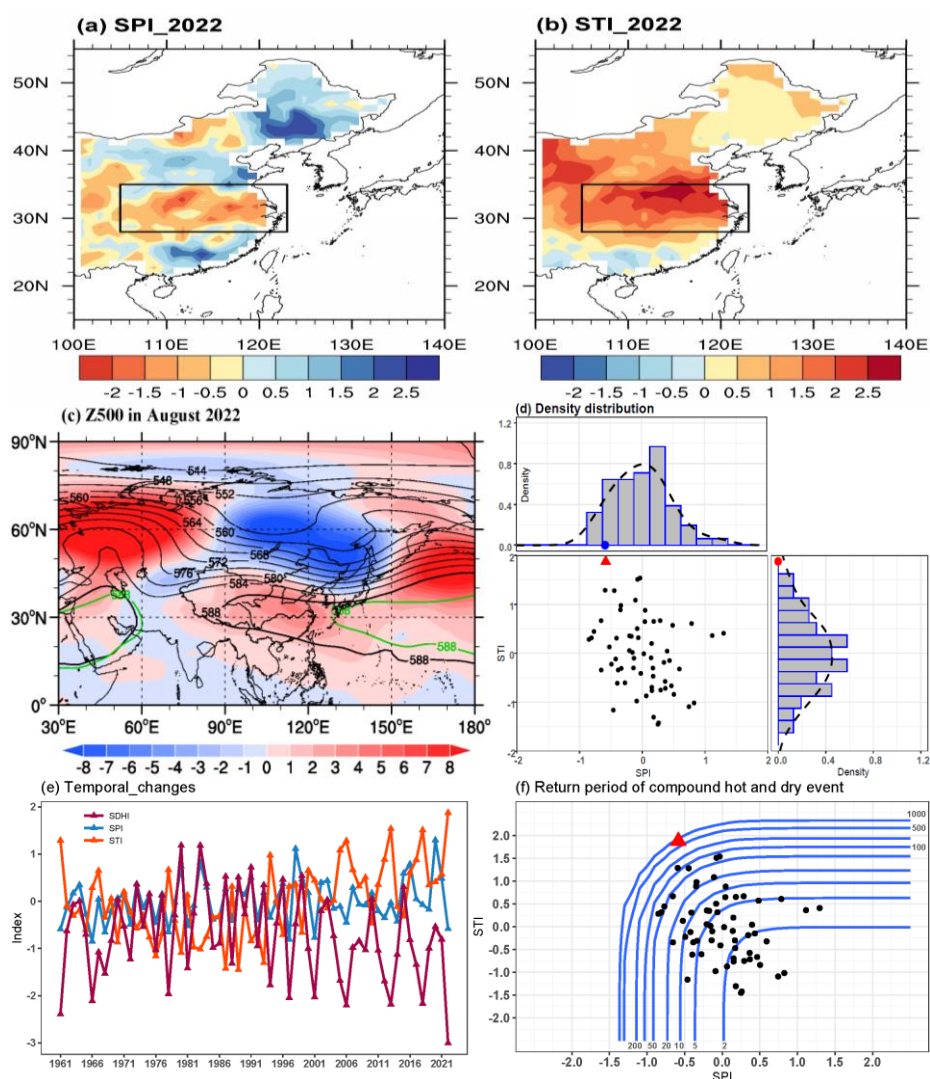


Figure 1. The summer 2022 compound event in its different aspects. (a and b) Spatial patterns of SPI (a) and STI (b) in East China to illustrate the event, the black box denotes the Yangtze River basin. (c) 500 hPa geopotential height (contours, dagpm) and anomalies (shading, dagpm), and the 588 dagpm contours (black solid line) and climatology (green line) for August of 2022. (d) The scatter plot of domain-averaged SPI and STI over the Yangtze River basin, the 2022 is shown as a red triangle, the upper and right side represent the distribution (gray bar) and estimated PDF (black dashed line) for SPI and STI, respectively. The blue and red solid points represent the 2022 event. The PDF is smoothed by a kernel density function with 100 equally spaced points. (e) Time series of domain-averaged STI, SPI and SDHI from 1961 to 2022. (f) The return period of compound event (solid line) based on optimal copula function (Frank copula).

The performance of models in simulating STI and SPI over the Yangtze River basin is firstly assessed before conducting the attribution analysis. The CMIP6 models can well simulate the increase in severity of compound event since 1990s with a weak interannual variability (Figure S2a). The CMIP6 models can also simulate the probability distribution of observed SPI and STI quite well, as shown in Figure S2b, c. The distributions of both STI and SPI in the model and observation cannot be

distinguished with the K-S test ( $p$  value  $> 0.05$ ). Then, we compare the probability of STI and SPI events similar to the one in 2022 in ALL and NAT simulations to quantify the impact of anthropogenic factor. For STI, the ALL forcing causes the PDF to generally shift to the right (Figure 2a). Under NAT forcing, the probability of a heatwave event similar to the 2022 event is very low, estimated at 0.00035. However, under ALL forcing, this probability increases to 0.0087. In other words, human influence has increased the probability of the record-breaking heatwave in 2022 by nearly 25 times and explained 96% (90% CI: 90%, 99%) attributable risk for the event (Figure 2d).

For SPI, anthropogenic forcing causes the entire PDF to shift to the left, indicating that anthropogenic forcing enhances dryness in the Yangtze River Basin (Figure 2b). Under NAT forcing conditions, the probability of a dry event similar to the 2022 event is 0.073. Under ALL forcing, this probability increases to 0.107. The risk of a dry event in the Yangtze River Basin reaching or exceeding the intensity of 2022 under historical forcing is nearly 1.5 times larger compared to natural forcing, of which 32% (90% CI: 21%, 42%) can be attributed to human influence (Figure 2d).

For the compound event (Figure 2c), the 2022 like compound event has a high recurrence interval of nearly 3500 years under Natural world, whereas it is much more frequent 1-in-500 years in the Actual world. Human activities have increased the likelihood of this record-breaking compound event by 7 times, of which 85.5% (90% CI: 66%, 96%) can be attributed to human activities (Figure 2d). When compared to FAR for STI, it is evident that the occurrence of this compound event is predominantly driven by heat induced by anthropogenic influence.

It is worthy of note that such conclusions couldn't be directly extrapolated to future scenario. Actually, we also performed the same analysis (results shown in Figure 2e, f) with historical (1961-2020) and SSP2-4.5 (2041-2100) simulations of the same models as we used to deal with the pair NAT/ALL. As expected for STI, the probability for heat increases from 0.0087 in "historical" to 0.97 in "SSP2-4.5". It is a little surprising to see that for SPI the probability of dryness decreases from 0.107 to 0.038, showing rainfall increases in the last half of the century (Figure 2e). This is consistent with most other studies investigating future rainfall changes in the Yangtze River basin (Wang et al., 2014), a consequence of enhanced East Asian summer monsoon (EASM) circulation. We suspect that the drying in ALL (compared to NAT) was mainly provoked by the important aerosol forcing, as demonstrated in Zhang et al. (2020) and Qian et al. (2009). The aerosol effects that contribute to the weakening of the EASM under ALL forcing have also been accounted for in CMIP6 models (Monerie et al., 2022). The likelihood of compound hot and dry event, similar to the one in 2022, is expected to increase in the Yangtze River Basin (Figure 2f), the return period from the historical and future show a considerable shift from 1-in-500-year to 1-in-27 years. Nevertheless, these events are projected to be less severe in term of dryness compared to the historical period, indicating that the compound event is primarily driven by heat, rather than dryness.

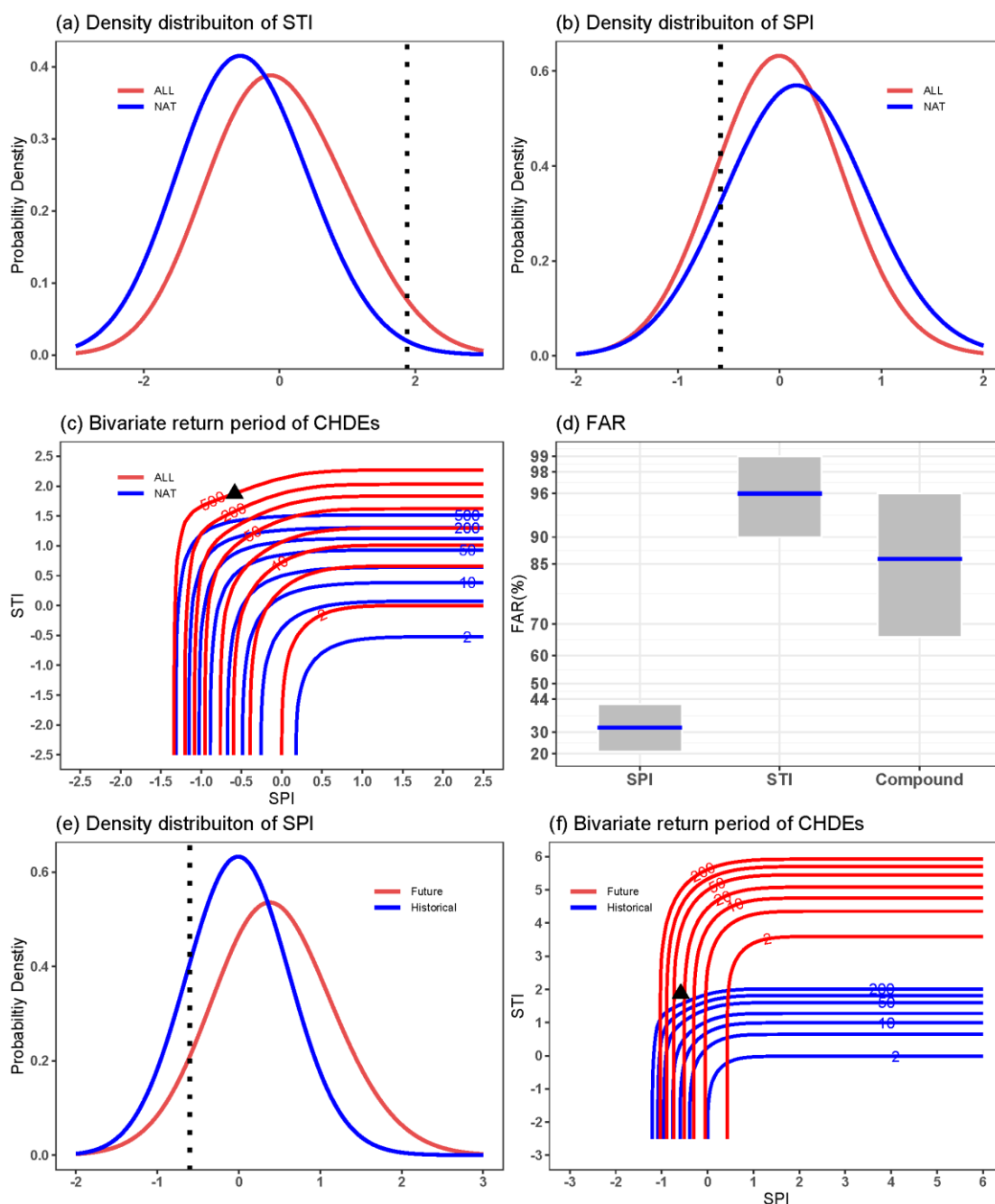


Figure 2. Attribution and projection results. The probability density function (PDF) of domain-averaged STI (a), SPI (b), and bivariate return period of compound event (c) for ALL forcing (red line) and NAT forcing (blue line), the selected copula function is Rotated Clayton 270 degrees for NAT and Rotated and Tawn type 1 90 degrees for ALL, respectively. (d) The best estimation (blue line) and 90% confidence interval (gray shadings) of the fraction of attributable risk (FAR) for SPI, STI and compound event. The PDF of domain-averaged SPI (e), and bivariate return period of compound event (f) for historical forcing (blue line) and future SSP2-4.5 forcing (red line), the selected copula function is Rotated Clayton 270 degrees for future. The black dashed lines and triangles denote 2022 event.

Dry conditions are generally favorable for hot event to occur, since the surface



energy partition is altered. It is thus interesting to investigate the occurrence probability of a hot event like that of 2022 under given dryness, and the fractional contribution of human activities to this conditional event. We found that human activities indeed increased the likelihood of hot event (STI being greater than 1.88) given dry conditions (SPI being -0.6). The probability of this conditional event is 0.0052 for natural forcing. It increases to 0.017 for historical forcing (Figure S2a). This gives a FAR of 70% (90% CI: 41%, 95.7%), implying that the anthropogenic influence explains 70% attributable risk for this conditional event. Additionally, we found that best estimated FAR of the conditional event increases as STI increases (Figure S2b), which means that human influence may lead to the occurrence of more intense hot event.

## Conclusions

In the summer of 2022, an exceptional hot and dry compound event occurred in the Yangtze River Basin in China. We found that anthropogenic effects have increased the occurrence probability of both heat and dryness as independent event, and the compound event involving them together. Specifically, a fraction of 32% (FAR) for the individual dryness and a fraction of near 96% for the individual heat is attributable to anthropogenic forcing. For the compound event, the fraction of attributable risk in relation to human activities is 86%. Based on the attribution, the compound event is primarily driven by heat, rather than dryness. This is even more evident for the future, as the probability of dryness occurrence will decrease in this region, while the probability of compound event will continue to increase.

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