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Anthropogenic Influences on Extremely Persistent Seasonal Precipitation in Southern China during May–June 2022

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Precipitation in southern China during April–June 2022 was the highest since 1961. Anthropogenic forcing has reduced the probability of 2022-like Rx30day precipitation by about 45% based on CMIP6 simulations.

The first rainy season, which usually extends from April to June, is an important contributor (40%–50%) to the total annual precipitation over southern China (Gu et al. 2018). From 22 May to 20 June 2022, six severe precipitation events occurred in southern China with the regional averaged precipitation anomaly being nearly 80% higher than the 1961–2010 climatology. These extreme precipitation events caused at least 37 deaths, affected 6.5 million people, collapsed over 9,200 houses, damaged around 24,000 houses, and affected 288.4 thousand hectares of crop fields (www.mem.gov.cn/xw/yjglbgzdt/202301/t20230112_440396.shtml). The direct economic loss was estimated to be more than 27.82 billion RMB (4.05 billion USD). This persistent heavy precipitation event was selected as one of the top-10 weather and climate events (www.chinanews.com.cn/gn/2023/01-09/9930883.shtml) as well as one of the top-10 national natural disasters of 2022 (www.mem.gov.cn/xw/yjglbgzdt/202301/t20230112_440396.shtml). This study aims to quantify the impact of anthropogenic activities on the likelihood of extreme precipitation events similar to the April–June 2022 event over southern China.

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Data and methods

Daily precipitation observations in the study region (280 stations, 23°–28°N, 109°–120°E) for 1961–2022 were obtained from China National Meteorological Information Center (Yang and Li 2014), using ~2,400 stations over China with quality control. We used the daily horizontal winds and specific humidity from ERA5 (Hersbach et al. 2020) to analyze circulation and moisture transport. We used 38 ensemble members from 8 CMIP6/DAMIP models (Eyring et al. 2016) under historical forcing (extending to 2020 by using the shared socioeconomic pathway SSP2–4.5 scenario, hereafter as ALL), natural forcing (NAT), greenhouse gas forcing (GHG), and anthropogenic aerosol forcing (AA) to investigate the impact of anthropogenic, GHG, and AA forcings on the probability of sustained extreme rainfall events over southern China in 2022 (Table S1 in the online supplemental material). The sea surface temperatures and atmospheric and land conditions of CMIP simulations are not synchronous with observational data, making it impossible to use CMIP simulations to evaluate a specific year. Therefore, we have selected the period 2011–20 as present-day climate (with the natural forcing run ending in 2020) (Christidis and Stott 2015; Lu et al. 2022). All simulations were interpolated to the 1° × 1° grid using bilinear interpolation. Daily precipitation, monthly horizontal winds, and specific humidity were used for analysis.

Extreme precipitation events of different durations (Rx*N*day, N = 1, 7, 14, 30), based on the regional mean maximum cumulative rainfall for April–June, were represented by the extreme precipitation index Rx*N*day, used in previous event attribution studies (Sun and Miao 2018; Yuan et al. 2018; Zhang et al. 2020). To reduce impact of model systematic biases in simulating the mean precipitation and variability, precipitation indices were expressed in normalized anomalies relative to the 1961–2010 climatology and standard deviation (Sun et al. 2019; Zhang et al. 2020). The climatology and standard deviation were calculated from observations/the ALL forcing runs. The ensemble means and mean standard deviations from all members were used for those models with multiple ensembles. Exceedance probability for 2022-like Rx*N*day extreme events were estimated from generalized extreme value (GEV) distributions (Jenkinson 1955; Ailliot et al. 2011) fitted to the distribution of precipitation indices. A two-sample Kolmogorov–Smirnov (K–S) (Hodges 1958) test with a significance level of 0.05 was used to test whether distributions of observed and simulated precipitation indices during 1961–2014 were from the same population. The occurrence probability of a precipitation event similar to the 2022 event (as a threshold) is denoted as P_{ALL} and P_{NAT}, for the ALL and NAT ensembles, respectively. The probability ratio (PR) was calculated from $P_{\mathrm{ALL}}/P_{\mathrm{NAT}}$ to quantify the changing likelihood of the 2022-like precipitation extremes due to anthropogenic influences. PR uncertainty with 95% confidence intervals (95% CI) was estimated by bootstrap in 2000 resamples of model ensemble members to determine the empirical 2.5th and 97.5th percentiles (Christidis et al. 2013). Doing each bootstrap, model ensemble simulations are randomly resampled with replacement to get a set of new data with the same ensemble sizes (38 × 10 = 380) as the original.

Results

During 22 May to 20 June 2022 (Fig. 1a), the regional averaged precipitation anomaly relative to the 1961–2010 climatology was nearly 80% higher than the 1961–2010 climatology and the anomaly was 2.49 standard deviations, making it the highest since 1961 with record broken precipitation in many stations (Figs. 1a,c) (Sheng et al. 2023), corresponding to a 1-in-62-yr event (Fig. 1d). The analysis of other precipitation indices shows that the observed 1-, 7-, and 14-day events have all recorded wetter conditions, corresponding to 1-in-6-, 1-in-16-, and 1-in-31-yr events, respectively (Fig. 1d). The extreme precipitation events in 2022 were associated with anomalous vertically integrated northward and northeastward moisture transport and

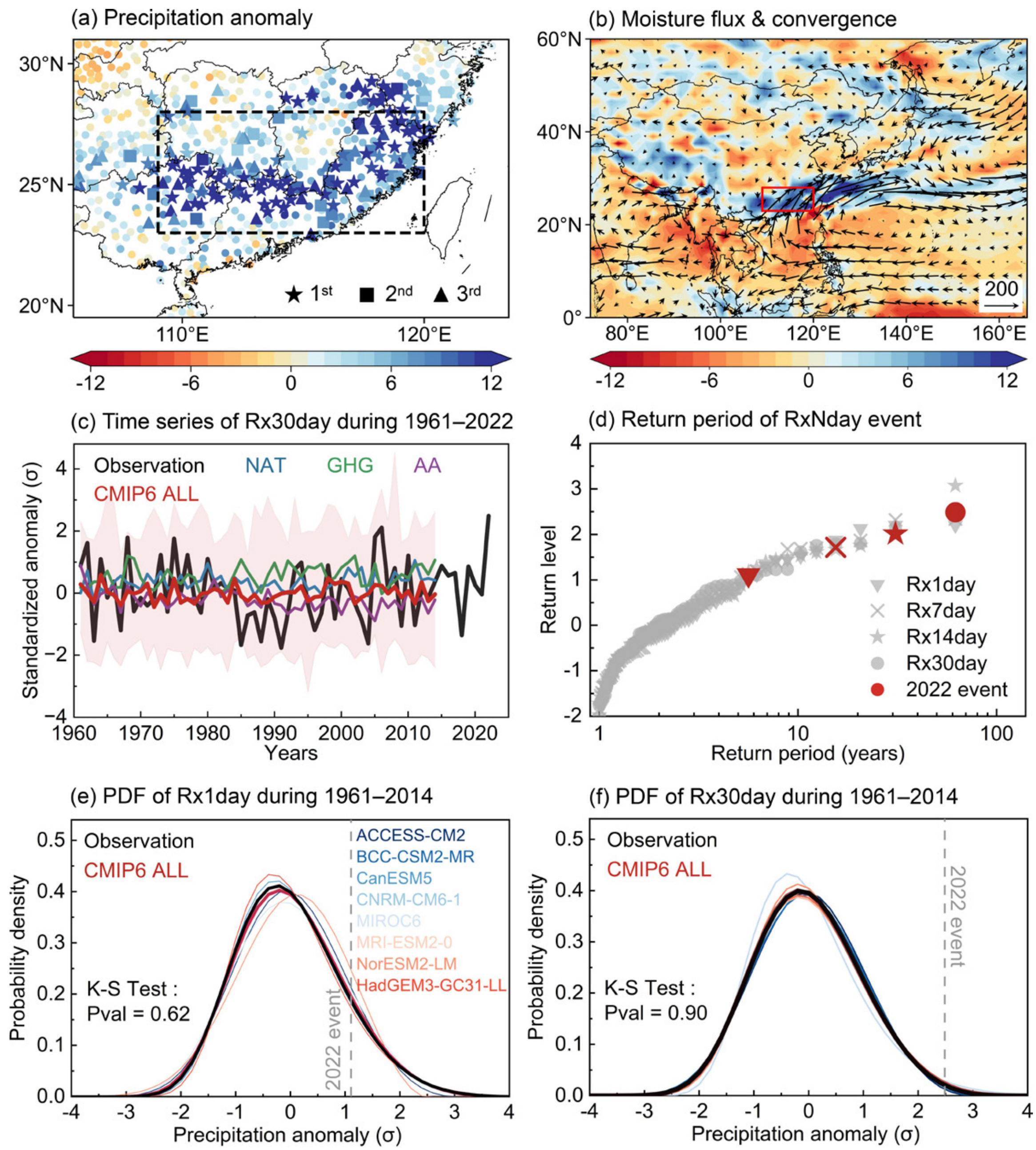

Fig. 1. (a) Observed precipitation anomalies (mm day^{-1}) during 22 May–20 June 2022 relative to the 1961–2010 climatology with symbols showing stations with first, second, and third highest anomalies since 1961 and (b) vertically integrated moisture flux (vectors; kg m^{-1} s^{-1}) and convergence anomalies from 1,000 to 100 hPa (shading; mm day^{-1}) during 22 May–20 June 2022 relative to 1961–2010 climatology with southern China (23°–28°N, 109°–120°E) outlined. (c) Time series of normalized observed, ALL, GHG, and AA forcing multimodel ensemble mean Rx30day indices in April–June over southern China relative to corresponding 1961–2010 climatology with shading indicating ALL forcing model spread. (d) Empirical return periods of RxNday in April–June estimated from observations. GEV fitted PDFs of (e) Rx1day and (f) Rx30day indices in April–June for observations and CMIP6 ALL (multimodel ensembles and individual model ensembles).

anomalous moisture flux convergence in southern China, related to the intensification and westward shift of the western Pacific subtropical high (WPSH) (Fig. 1b).

It is clear that the model covers most of the observed range of Rx30day in southern China (Fig. 1c). The Rx1day and Rx30day anomalies exhibit similar distributions between simulations and observations (Figs. 1e,f) with p values of 0.62 and 0.90, respectively, according to the two-sample K–S test. Overall, the models can be considered reliable for the attribution of extreme precipitation events in 2022.

To quantify anthropogenic influences on 2022-like extreme precipitation risk, probability density functions (PDFs) of precipitation indices among different forcing simulations were compared. For Rx1day, PDF in ALL shifts toward higher precipitation anomalies in comparison with that in NAT (Fig. 2a). Specifically, the probability of Rx1day similar to 2022 event increases from 0.15 (95% CI: 0.14–0.18) in NAT to 0.18 (95% CI: 0.13–0.21) in ALL (Table S2) with PR of 1.24 (95% CI: 0.91–1.65, Fig. 2e), corresponding to a change in the return period from around a 1-in-8-yr event in NAT to a 1-in-5-yr event in ALL (Fig. 2c). However, the result is insignificant due to the confidence interval (CI) including 1.0, showing there is uncertainty whether the event is getting more or less likely. In contrast, PDF for Rx30day in ALL exhibits a shift toward

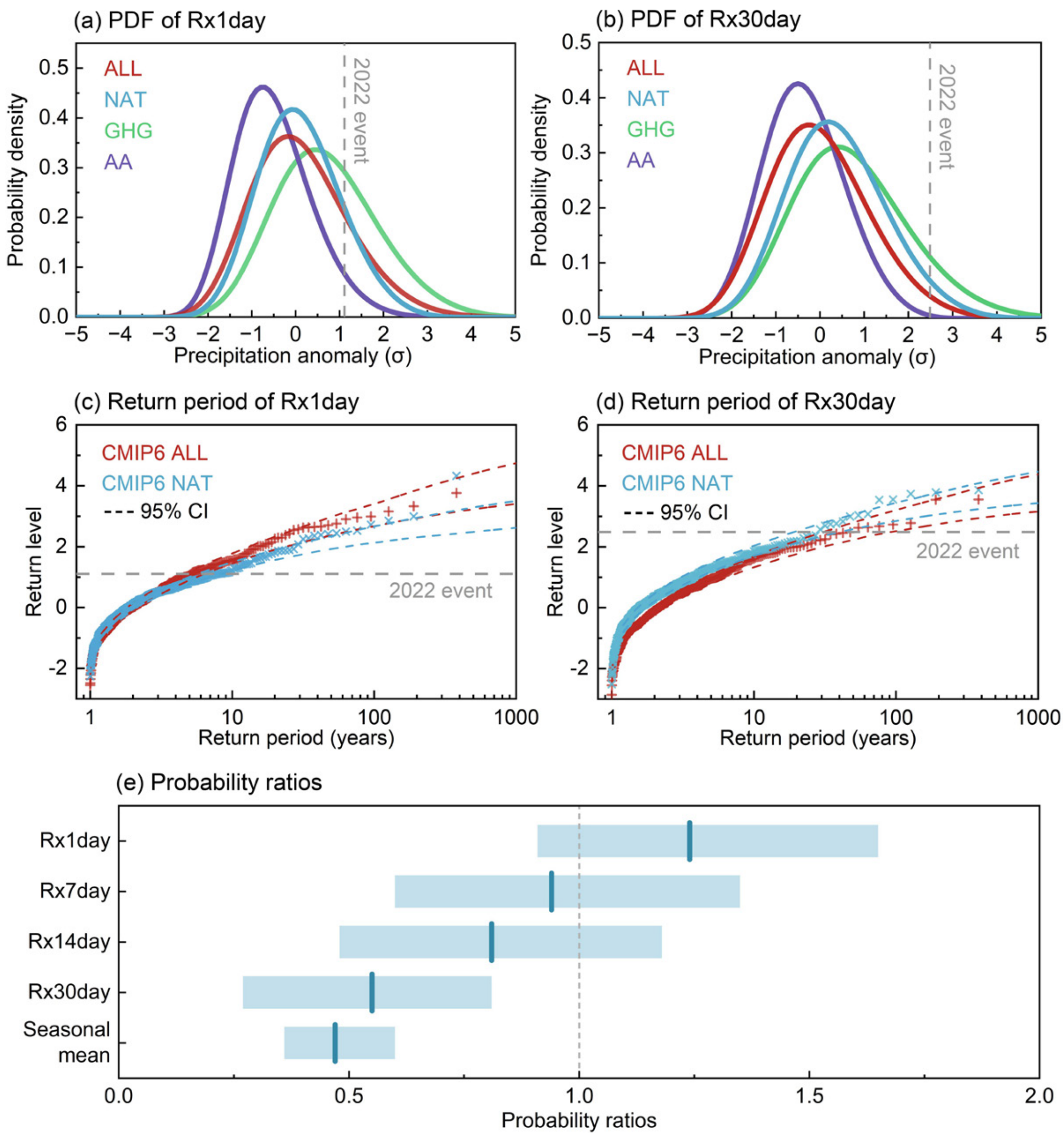

Fig. 2. GEV fitted PDFs of precipitation indices for CMIP6/DAMIP model ensembles with ALL (red), NAT (blue), GHG (green), and AA (purple) simulations for (a) Rx1day and (b) Rx30day events in April–June over southern China during 2011–20. Return periods of (c) Rx1day and (d) Rx30day events in GEV fit with 95% uncertainty range estimated from the CMIP6 model ensembles. (e) Probability ratios (vertical line) with the 95% confidence interval (shaded) for RxNday events and seasonal mean.

negative precipitation anomalies compared to NAT (Fig. 2b). Specifically, anthropogenic effects reduce the probability of the 2022-like Rx30day event from 0.04 (95% CI: 0.02–0.06) to 0.02 (95% CI: 0.01–0.03) (Table S2) with PR of 0.55 (95% CI: 0.27–0.81) (Fig. 2e). Thus, the likelihood of sustained heavy precipitation similar to the 2022 Rx30day is reduced by about 45% (19%–73%) in the region due to anthropogenic effects, corresponding to an increase in return period from a 1-in-29-yr event in NAT to a 1-in-48-yr event in ALL (Fig. 2d).

Further clarification of the different contributions of GHG and AA in contributing to precipitation extremes would improve understanding of the attribution results. Figures 2a and 2b illustrate that PDFs of Rx1day and Rx30day indices in GHG simulations are flatter and shift to the right in comparison with NAT, indicating a trend toward a wetter condition, while PDFs in AA simulations are narrower and shift toward a drier condition. GHG influences on Rx1day overwhelm AA influences, leading to increase of the likelihood of Rx1day similar to 2022 from NAT to ALL. In contrast, the decrease of the likelihood of Rx30day from NAT to ALL is predominantly due to AA forcing. Physical processes of different forcings on Rx30day are further investigated. The normalized Rx30day and April–June seasonal mean precipitation indices are highly correlated with a correlation coefficient of 0.85. The variability of Rx30day interannual variations explains 53% of the variability of April–June precipitation. In addition, PDFs of Rx30day and seasonal mean precipitation indices show similar distributions (Fig. S1). Therefore, to understand the attribution and associated atmospheric circulations with the reduced probability of 2022-like events, differences in the April–June seasonal mean atmospheric circulation under different forcings were analyzed. Results reveal that reduced seasonal mean precipitation occurs over southern China in ALL compared to NAT in 2022 (Fig. S2a). This reduced precipitation is associated with anomalous northerly winds, corresponding to weakened southerlies and reduced moisture transport (Fig. S2b). Precipitation was intensified by GHG forcing in the northern part of southern China (Fig. S2c), which is associated with warm and moist air transported by anomalous southwesterly winds from the Indian Ocean (Fig. S2d). Precipitation is severely reduced by AA forcing (Fig. S2e), resulted from reduced water vapor transport from the Indian Ocean to southern China (Fig. S2f). The WPSH is a key circulation system controlling summer monsoon and typhoon activity in the western Pacific, but there still remains a significant uncertainty in predicting its future changes (Chen et al. 2020).

These findings are consistent with the attribution results of C. Li et al. (2018), Lu et al. (2021), and Zhang et al. (2020), which reported that anthropogenic influences reduce the likelihood of persistent precipitation extremes during the warm season. Previous studies have also pointed out different influences of GHG and AA on persistent heavy rainfall (X. Li et al. 2018; Westervelt et al. 2020; Zhou et al. 2021). According to the Clausius–Clapeyron relation, GHG forcing leads to atmospheric warming, resulting in an increase in atmospheric moisture (Li et al. 2017; Zhou et al. 2021). Climatologically, the increase in atmospheric moisture favors more intense rainfall events, which is evident across East Asia. In contrast, AA typically weakens the occurrence of persistent heavy rainfall events over East Asia. This is related to the cooling effect of AA in the atmosphere. On the one hand, the cooling in the atmosphere reduces atmospheric moisture, which weakens precipitation events thermodynamically. On the other hand, the larger cooling anomaly over land weakens the land–sea thermal contrast, leading to a weakening of associated circulation patterns. This is expected to dynamically suppress heavy rainfall (Li et al. 2016; Wu et al. 2016; Zhou et al. 2020). Li et al. (2015) suggests that rainfall decreases under AA forcing and increases under GHG forcing. Thus, the total change depends strongly on the relative strength of the two competing effects. AA forcing dominates over the GHG effect during the historical period, leading to the general drying trend in the All forcing simulations. While the thermodynamic change of mean moisture convergence in the ALL forcing is dominated by the GHG forcing, the dynamic change of mean moisture convergence in the ALL forcing is dominated by the AA forcing. However, the attribution result from this study is not analogous to what may happen in the future with projected reduced aerosols. Further assessment of future risks for the 2022-like events needs to be explored and this is important for the development of mitigation and adaption decisions to reduce the potential impacts.

Conclusions

Using large ensembles of CMIP6 models, anthropogenic influences on changing risks of the 2022 April–June extreme precipitation in southern China were quantified. Attribution analysis suggests that anthropogenic forcing reduces the likelihood of a persistent severe precipitation event (Rx30day) in April–June 2022 by approximately 45% (19%–73%), predominantly caused by AA forcing. The likelihood of daily extreme precipitation events increased in the model due to anthropogenic forcing, but this change was not statistically significant. We conclude that the unusually high rainfall (Rx1day) during April–June 2022 in southern China is not attributable to anthropogenic forcing, at least based on the CMIP6 historical simulations. Therefore the 2022 extreme 30-day mean precipitation could be a manifestation of natural variability. Since increasing GHG has a positive influence on 30-day mean precipitation in the region, and AA emissions are expected to decline, future observations and updated historical simulations should be used to monitor the region for the possible emergence of an increasing 30-day precipitation rainfall signal in the future.

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Data availability statement. The following data are available online: the CMIP6 simulations (https://esgf-node.llnl.gov/projects/cmip6/), the ERA5 data (www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5/), and the homogenized station data in China (http://data.cma.cn/).

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